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Developing a Joint Army/Navy Coastal Wave Prediction Program–A Planning Report

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13. ABSTRACT *(Maximum 200 words)*

This planning report presents a technical summary and recommendations for jointly developing improved coastal wave prediction capabilities for the Army and Navy, and was prepared by the Army/Navy Wave Prediction Group. Wave-related physical processes are crucial for both Army and Navy operations, such as mine, amphibious, and logistics over the shore. Current coastal wave prediction capabilities are inadequate to meet several critical nearshore operational requirements. Nearshore physical environments are intrinsically more complicated than deep water due to strong interactions of waves with currents and irregular bathymetry. Important dynamic processes include wave shoaling, refraction, diffraction, and energy dissipation through wave breaking and bottom friction. Attention must be given to wave-driven nearshore processes, which in turn influence wave conditions. The fine-resolution (both spatial and temporal) coastal wind forecasting plays an equally central role in this endeavor. Coupled with the increased complications of the coastal regions is the stringent requirement that many DoD coastal littoral warfare requires a higher level of accuracy than deep-water counterparts.

This report presents a technical strategy with a vertically integrated approach for improving DoD wave prediction capabilities to advance current state-of-the-art. The strategy encompasses theoretical and experimental studies, comprehensive new field measurements, numerical modeling, and operational validation/evaluation/modification. Substantial common interests currently exist between the Army and Navy, thus a new R&D program jointly funded and executed is deemed to be timely and cost effective. The final deliverable of this joint program will be an improved integrated coastal wave prediction system for Army and Navy operational needs.

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Executive Summary

This planning report presents a technical summary and recommendations for developing jointly improved coastal wave prediction capabilities for the Army and Navy. The clear and urgent need for this effort results from two related situations - first, DoD's increasing emphases on littoral warfare after the end of cold war that had centered on blue-water Anti-Submarine Warfare (ASW), and second, longtime relatively low level efforts in research/development on shallow water waves in coastal areas. Wave-induced physical processes are crucial for both Army and Navy operations, such as Mine Counter Measure (MCM), amphibious, Logistics Over the Shore (LOTS), and special warfare that employ various acoustical, optical and E-M sensors and weapons, in both in-situ and remote sensing modes. Current Army and Navy coastal wave prediction capabilities are inadequate to meet several critical operational requirements.

This report reflects comprehensive discussions during and after four meetings held since July 1994 involving many personnel from Army (Waterways Experiment Station, WES), Navy (Office of Naval Research, ONR; Naval Research Laboratory, NRL; Naval Oceanographic Office, NAVOCEANO; Fleet Numerical Meteorology and Oceanography Center, FNMOC) and universities which clearly revealed considerable deficiencies in understanding of nearshore wave physics. Details of these assessments are included in the following four chapters of this report with further details in several appendices. Nearshore physical environments are intrinsically more complicated than deep water, due to strong interactions of waves with currents, and irregular bathymetry. Important dynamic processes include wave shoaling, refraction, diffraction, and energy dissipation through wave breaking and bottom friction. Attention must be given to wave driven nearshore processes; which in turn influence wave conditions. The fine-resolution (both spatial and temporal) coastal wind forecasting plays an equally central role in this endeavor as well. Coupled with the increased complications of the coastal regions is the stringent requirement that many DoD coastal littoral warfare requires a higher level of accuracy than the deep water counterparts.

The Army and Navy needs the capability to estimate wave conditions in coastal water over a wide range of temporal and spatial scales and includes both operational and planning horizons. The Army/Navy Wave Prediction group recognized that wave predictions can be accomplished through a variety of means: physics-based wave prediction models, extrapolations of observations, empirical correlation techniques and believe that in the correct instances each can be appropriate. The Army-Navy group is primarily composed of wave modelers whose tasking has been to establish predictive models within DoD and hence this report reflects this orientation. However, the group consistently emphasized the need to couple observations and models with the goal of providing the best information that can be deduced from each.

Review of existing DoD wave prediction technology and R&D efforts and recommendations provided by our scientific panel lead to a three prong strategy that will improve the quality of DoD coastal wave predictions. The first element is development of a joint Army and

Navy wave prediction system which combines the best features of both services wave prediction technology into a modular system that can be readily updated with the results of the Army and Navy research programs. The system must be flexible to accommodate the many diverse needs of the two services and the wide range of operational scenarios in which wave predictions may be made. This effort would also include a program of continuing model performance evaluation and testing. The second element calls for the enhancement of fundamental wave research with particular emphasis on those studies that are expected to improve the representation of source/sink and energy transfers terms in the energy balance equations and the energy propagation algorithms that are the heart of forecast model technology. This element calls for a series of field experiments to address the interaction of fundamental processes governing wave field evaluation. The third element recognizes that coastal waves are extremely dependant on site specific, local conditions and that first principle's models driven purely by atmospheric forcing may not be sufficiently accurate. This effort calls for the collection of site specific data in areas of critical DoD interest and the development of systematic approaches for collecting and infusing observational data (gathered by in situ instruments or via remote sensing) into the wave prediction system.

It is worthy to note that much of future advances and improvements to be made in coastal wave prediction capabilities shall have major contributions to regional- and global-scale wave predictions as well. This positive feedback is important because, in fact, the prediction from these larger areas are often the required input boundary conditions to the smaller area coastal predictions.

The report presents a technical strategy with a vertically integrated approach for improving DoD wave prediction capabilities to advance current state-of-art. The strategy encompasses theoretical and experimental studies, comprehensive new field measurements, numerical modeling and operational validation/evaluation/modification. In order to use effectively technical resources and specialties currently scattering among various federal agencies and universities and to minimize duplications, a horizontally integrated approach will be equally important. Substantial common interests currently exist between Army and Navy, thus a new R/D program jointly funded, and jointly executed is deemed to be realistic, timely and cost-effective for DoD. The final deliverable of this joint program will be an improved integrated coastal wave prediction system for Army and Navy operational needs.

I. INTRODUCTION

The Department of Defense has longstanding requirements for wind wave predictions both on the open ocean and in the littoral region (Table 1) that are critical for both planning and operations during war and peace. Until recently, DoD wave prediction has been focussed on the deep ocean consistent within the existing operational needs of the Navy: More recently the end of the cold war has significantly altered DoD strategies for dealing with perceived threats to U.S. security; that in the Navy has lead to increased emphasis on Littoral Warfare and in the Army has rekindled interest in rapid force deployment and Logistics Over the Shore operations. Consequently both the Army and Navy now have significant interests in the coastal or littoral environment and new needs for improved coastal wave predictions.

The new interest in littoral warfare has created two notable differences in research directions within DoD. First, due to the lack of past emphasis, shallow-water prediction capabilities are substantially diminished from those in deep water. Second, whereas, deep-water oceanic predictions were predominantly a Navy interest, predictions in shallow water are not. In this area both the Navy (NRL, NAVOCEANO, ONR, and FNMOC) and the Army (WES) have a common interest and prognosis. The recognition of both overlaps in research objectives and the lack of existing capabilities in shallow-water predictions provided the impetus for the formation of the Army-Navy Wave Prediction Group (AN-WPG) whose members are listed in Appendix A. The goal of the AN-WPG has been to review wave prediction efforts in DoD and develop a coordinated approach to improve DoD coastal wave prediction capabilities to meet Army and Navy requirements. The Army-Navy Wave Prediction Group grew out of a series of individual collaborations into a longer term effort to more formally produce a joint technology to meet the needs of both services. It has grown to include advice and discussion by a wider group of academics and research scientists from other government laboratories. The AN-WPG has and will actively seek out other groups such as the WISE group (Waves In Shallow Environments) which includes European, U.S., Australian, and Asian participants that have similar interests where coordination or technical interchange would be beneficial.

Navy interests in operational wave predictions can be separated into three main categories:

(a) PREPOSITIONING - transit of large combatants and utility vessels across large ocean basins into a relatively small region. This requires large scale predictions with skill required in accurately identifying the low frequency wave energy affecting ship routing and pitch and roll limitations critical to certain weapon and sensor systems. Important areas to support include:

1. High seas warnings,
2. Input to acoustic models, optics systems.

(b) REGIONAL OPERATIONS - Operating in a regional domain supporting a nearshore operation. This involves operating combinations of large and medium craft. Important areas to support include the following:

1. High seas warnings,
2. Operating thresholds of medium and small craft,
3. Input to acoustics, optics, oil spill forecasts.

(c) NEARSHORE OPERATIONS - Conducting tactical operations in shallow water near the shore. This is the most complex area of support and involves, but is not limited to, the following:

1. Operating thresholds of small craft and amphibious vehicles,
2. Operating thresholds of swimmer operations,
3. Surf boundary conditions with high confidence in initial wave energy direction,
4. High resolution modeling of complex bathymetry, shoreline configuration, islands, bays, and sounds,
5. Harbor and inlet models with boundary conditions,
6. Real time assimilation of remotely sensed data along boundaries of nearshore models,
7. Coupling of wave and tide models to account with varying depth and wetted surface area,
8. Forecast surf conditions for amphibious landings and swimmer operations,
9. Coupling of nearshore wave models to circulation models.

Army needs for wave predictions are predominately in the coastal zone related to Logistics Over the Shore. In many areas of the world, existing port and harbor facilities are inadequate to handle large military operations; and where sufficient port facilities presently exist, it is possible that they may be heavily damaged or strongly fortified before an operation begins. Therefore, accurate prediction of environmental phenomena in coastal areas is now of prime importance to many joint and single-service operations. As an example of some of these needs, the Army Strategic Mobility Plan has been initiated to address conclusions of the Mobility Requirement Study (MRS). An essential element of these conclusions is that the military can only increase its deploy ability through an expanded investment in sealift and airlift, prepositioning, and transportation infrastructure. Some mobility standards developed under the Army Strategic Mobility Plan require that

1. an afloat heavy combat brigade with support must close into the theater and be ready to fight not later that 15 days after commencement of action (C+15), and

2. two heavy divisions to include the logistical support structure must close in the theater by C+30.

The requirement to support this level of mobility increases the likelihood that LOTS operators may be required. Army coastal wave needs largely parallel the Navy Nearshore Operators' requirements listed above.

Besides having a direct, pronounced effect on coastal operations involved in amphibious assaults, force projection and LOTS, wave conditions and related bathymetric responses also effect a wide range of related operations such as mine warfare and mine counter warfare, obscurity of targets to acoustic and optical sensors, special operations, and nearshore construction, just to name a few. All of the operations listed above are extremely sensitive to wave conditions.

The experiences of the Army and Navy wave prediction community over the past five years suggest that although deep ocean wave prediction technology can still be significantly improved, its overall quality was significantly better than corresponding coastal capabilities. Hence the AN-WPG decided to emphasize coastal wave prediction as its fundamental priority. Coastal operations such as amphibious assaults and LOTS are particularly sensitive to waves, waves of 1 to 2 meters which are of little importance to many deep water operations can seriously disrupt or halt coastal operations. Table 2 provides examples of the impact of sea states with waves of more than 1 meter in recent joint LOTS exercise. Although amphibious operations can take place in larger waves, they are also significantly disrupted by prolonged exposure to sea states 3 or more.

In considering the level of skill required for coastal predictions, the AN-WPG focussed upon the joint LOTS operations as the critical determining operation, since most other coastal operations are no more sensitive in wave conditions. Since LOTS operations halt if waves exceed 1 meter, a goal of predicting coastal waves of about 1 m significant height with 20 cm rms error was insufficient. A review of a series of hindcast and forecast studies performed by members of the AN-WPG indicated typical forecast errors run 30-200 cm. Most of these studies were performed in deep water; the conclusion of the AN-WPG is that shallow water prediction models would probably increase the error as waves were transformed from deep water to the surf zone.

Successful predictions of wave conditions in the coastal zone involve a range of technologies and capabilities. These include numerical models, in situ and remote sensing measurement capabilities, theoretical and analytical procedures and statistical simulation techniques. Uplifting capabilities in each of these areas as well as integrating capabilities should be a R&D goal for both services. More emphasis is placed on developing and enhancing numerical prediction schemes because such systems form a natural link to the meteorologic forecast models which can be used in the critical traditional forecast role. Furthermore, the complexity of the coastal system may only rationally be treated in such a manner. However, it is important to recognize that simpler approaches may sometimes be warranted and appropriate, such capabilities should not be excluded from an R&D program. The fusing of measurements to update or refine model predictions coupled with the capability of the models to convert the information into forecasts represents the most efficient path for unproved predictions.

The Army and Navy wave prediction needs in coastal or littoral areas encompass a range of time, space, and technology needs. For example, long term mission planning or operational support may require simulation of the wave field days, weeks or even months in advance. In these cases normally a wave prediction model driven from a meteorological forecast or climatological description is used. Wave conditions during operations may depend upon models driven purely by weather information or may include wave measurements that have been assimilated into the prediction. Very near the coast however, particularly in regions of rough bathymetry, operational wave conditions may be very difficult to predict because the level of resolution of information is beneath the scale of that provided by typical wave and weather models. Unfortunately it is in these situations that the most accurate forecast capabilities (in absolute terms) are needed. Thus, wave prediction technology needs to include a provision for techniques such as empirical correlation between sensors and forecasts to provide the needed capabilities of computational platforms in a distributed mode (forecast center and on site). The emphasis on models is in recognition that for many predictive scenarios the translation of weather data into wave data is apt to play as big a role as in the past and in recognition that the understanding of the usefulness as well. The Army-Navy Wave Prediction Group stresses the need and usefulness of hybrid prediction systems (models plus data including site specific calibration) as a needed adjunct to the model technology. In the Strategy section to be presented at the end of this report includes hybrid approaches as a significant research goal.

The need for additional research in shallow-water is not service specific. Consequently, a joint effort to improve our capabilities will be much more efficient than two independent efforts occurring in parallel. This suggests that one of the major objectives of the AN-WPG should be to work toward the development of a joint integrated wave prediction model with an overall structure along the lines of that shown in Figure 1.

The structure of the remainder of this report will be as follows:

section 2: assessment of wave prediction model status;
section 3: improvement of wave prediction - research and development issues;
section 4: technical strategy for improving coastal wave predictions;
section 5: summary.

Table 1
DOD Needs for Wave Information

Prediction Mode	Navy Requirements	Army Requirements
Forecasts **&** **Nowcasts**	Ship Routing Amphibious Operations Logistics Over the Shore Harbor Conditions Input to Acoustics, Optics Models Input for Oil Spill Models Mine -Countermine Operations Other Than War	Logistics Over The Shore Dredging Operations Emergency Operations Operations Other Than War
Hindcasts *Climatologies* *Event Reconstruction*	Amphibious Assault Planning Contingency planning Risk Analysis	Logistics Over The Shore Site Selection Contingency Planning Risk Analysis Structure Design Shore Process Studies Emergency Planning
Simulation *Real or Synthetic Events*	Training War Gaming	Training War Gaming Structure Design Emergency Planning

TABLE 2

1. Sea-State-Related Problems Encountered During Recent JLOTS Exercises

   * Total throughput over the operation was far less than required for a successful JLOTS operation, due primarily to sea-state-related problems

   * Several lighters capsized during moderate wave conditions

   * Problems with barge connections disabled several barge units

   * Throughput essentially ceased when wave conditions approached 1 meter

   * Construction of key assets in a JLOTS operation is significantly delayed by wave heights approaching three feet

2. Bathymetry-Related Problems Observed During Recent JLOTS Exercises and Subsequent Experiments

   * Many vessels attempting to deploy supplies directly on the beach could not navigate over the nearshore bar

   * Bathymetric changes of up to 1.5 meter over a three-day period have been observed - such changes dramatically affect acoustic detection plans in coastal areas

   * Paths of floating mines are very dependent on wave-driven coastal currents

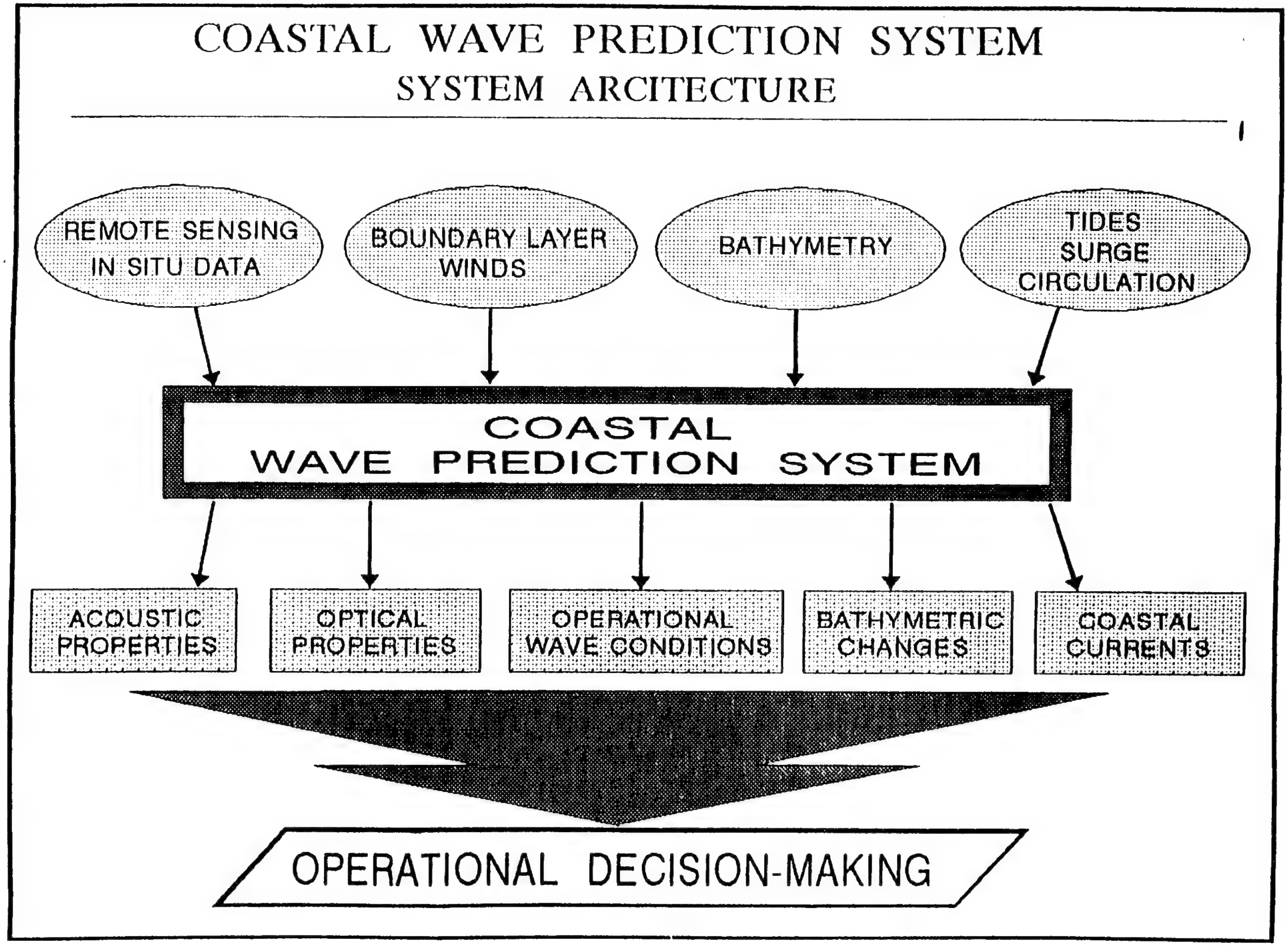

COASTAL WAVE PREDICTION SYSTEM
SYSTEM ARCITECTURE
REMOTE SENSING
IN SITU DATA
BOUNDARY LAYER
WINDS
BATHYMETRY
TIDES
SURGE
CIRCULATION
COASTAL
WAVE PREDICTION SYSTEM
ACOUSTIC
PROPERTIES
OPTICAL
PROPERTIES
OPERATIONAL
WAVE CONDITIONS
BATHYMETRIC
CHANGES
COASTAL
CURRENTS
OPERATIONAL DECISION-MAKING

FIGURE 1

II ASSESSMENT OF WAVE PREDICTION MODELS

1. Development Survey

We divide the oceanic domain into four regions for wave modeling purposes:

1. Global (oceanic, water depths > 1000m)
2. Regional (continental shelf zone, and semi-enclosed seas, water depths 15-1000m)
3. Nearshore (including surf zone and inlets, water depths < 15m)
4. Harbor

The current status of DoD efforts is briefly summarized below. Army and Navy wave-related projects are listed in Appendix B.

A. Global (Oceanic) Wave Modeling

Both the Army and Navy have been using a third generation spectral wave model called 3GWAM, (WAMDI, 1988) for global wave modeling for some time. 3GWAM was developed by a consortium primarily of European scientists from 1983-1993. Third generation models like 3GWAM are thought to be technically more sound, because the description of the source/sink mechanisms are based on the use of a discretely defined frequency/direction solution and not formulated on a parametric spectral shape. There are other third generation wave models (e.g. Tolman, 1989; Khandekar, 1989; Burgers, 1990) however, all are, in general, very similar to 3GWAM. FNMOC as well as NAVOCEANO have already implemented this model in their respective wave forecasting systems. In addition, the National Weather Service and the European Centre for Medium Range Weather Forecasts are using 3GWAM for wave forecasts. Second generation wave modeling (called WISWAVE) has been implemented for a long-term wave climatology study pursued by WES (Hubertz, 1992). Over the last seven years, WES has actively participated in the WAM Group (Komen et al., 1994), as well as investigated 3GWAM through the Surface Wave Dynamics Experiment (Weller et al., 1991). WES intends to eventually replace its second generation wave model in their hindcasting efforts after it completes an evaluation of 3GWAM's performance relative to existing wave modeling technology.

The 3GWAM is based on energy balance equation; with source/sink terms including the atmospheric input, nonlinear wave-wave interaction, and high frequency dissipation. In global modeling, the effects of water depth and currents are ignored. Wave evolution is dictated by synoptic meteorological conditions. Grid resolutions for oceanic applications are scaled toward 1°. Any island, or other geographical feature smaller than 1° must be considered as being sub-scale. Time scales dictated by meteorological input are nominally three hours, however for tropical storms, these may decrease to one hour. A time step of three hours may be considered as

too long (Resio, 1994), because the times at which significant directional spectral changes to various external forcing, are of order 30 minutes.

B. Regional Wave Modeling

The regional wave modeling is very similar to the global wave modeling. Additional processes include refraction, shoaling, wave-bottom effects, and depth induced breaking. The nonlinear wave-wave interaction is weakly nonlinear and encompasses a four wave interaction (Hasselmann, 1962).

The present modeling technology is 3GWAM with *shallow water* options activated. In 3GWAM and WISWAVE forecasting and hindcast systems, a multi-level grid nesting procedure is used by FNMOC, NAVOCEANO, and WES. The regional wave modeling domain include, continental shelf zones, as well as semi-enclosed (e.g. the Arabian Sea/Gulf of Oman, Gulf of Mexico) and fully enclosed (Mediterranean Sea, Great Lakes) water bodies. Horizontal grid size range from approximately 10 to 100 km, and time steps from 10 to about 60 min. The grid size must decrease as the water depth decreases. Based on these criteria, meteorology falls in the ranges of mesoscale, and micro-scales. Land-sea breeze effects, frontal passages, orographic effects resulting from bordering mountainous regions would also play an important role. In regions with very complicated bathymetry, a finer resolution grid or a nested modeling scheme may be required.

C. Nearshore Wave Modeling

The wave modeling for this area becomes far more complex than the above areas, because of rapid changing bathymetry and the higher order, nonlinear processes affecting wave conditions. In the nearshore region, wave modeling will also have to resolve the mechanism of nonlinear wave-wave interactions in the coastal region. There are many un-explored possibilities: three, four, and five wave interactions, and also the edge wave and surf beats interactions. Depth induced wave breaking mechanisms have to be included. For certain applications, the regeneration of the waves following the breaking process is also a critical mechanism. Nearshore waves are highly site-specific and are affected by local factors such as the shoreline configuration and hydrodynamic effects such as changes in the water level, small and large scale circulations, and micro-scale meteorological effects like the land-sea breeze effect. In the surf zone rapid changes of the beach and bar configuration causes significant change on wave conditions.

Grid size and time step are of the order of 10's to 100's of meters, and 10's of seconds, respectively. Computationally, this may prove to be highly restrictive, even with present high performance vectoried computer systems. Some models presently exist in Navy and Army are described briefly below.

a. RCPWAVE:	A monochromatic short period wave model solving the elliptic mild-slope equations to predict linear propagation over an open coastal region of arbitrary bathymetry. Considered in a class of Combined Refraction-Diffraction models.
b. REF/DIF 1 And REF/DIF S:	Shallow water wave models solving the parabolic mild-slope equations to estimate wave conditions in an open coastal region. (Kirby and Dalrymple, 1994, and Kirby and Ozkan, 1994)
c. STWAVE:	A time-independent spectral wave model solving the convective portion of the energy balance equation for spectral wave propagation over arbitrary bathymetry. It includes the effects of an atmospheric put, and nonlinear wave-wave interactions in a parametric form.
d. TESS Surf Model:	A surf zone model which predicts breaker statistics and longshore current given an incident wave field (in about 10 meters depth). The optional refraction-diffraction module used in the system is RCPWAVE. The Navy also uses this model with input outside the surf zone.
e. Boussinesq Wave Model	A time-dependent wave model that solves the continuity and momentum equations for the free surface and also flow field. The Army Research Office is presently sponsoring work performed by the Center for Applied Research at the University of Delaware. A model called GNWAVE (Demirbilek and Webster, 1992) based on Green-Naghdi theory of fluid sheets is also developed.
f. CGWAVE:	A time-independent finite element spectra model solving the elliptic mild-slope equation (Panchang et al., 1991). A spectral version is scheduled for completion in 1995 time frame.

The use and evaluation of so many nearshore wave models reflects two issues. First, there is no technical consensus on a generalized, widely applicable model for nearshore waves; each model reflects partial solutions to the problem. Second, field and laboratory data sets are inadequate to resolve the technical issues and questions satisfactorily.

D. Harbor and Inlet Wave Modeling

Although harbor waves and waves in inlets are important, no further discussions will be given in this report because they are traditionally very site specific and require different model approaches. As this technology evolves, these models can be coupled to the class of prediction techniques treated in this report. A summary of the status of harbor modeling is included as Appendix C.

2. Known Deficiencies:

Isolation of wave model deficiencies from errors in forcing functions, or geographical effects (e.g. wind input, current effects, water level changes, or bathymetric effects) is difficult. Hence, care is required in the evaluation of any wave modeling technology in regard to a measurement because of the unknown nature of these other contributing factors. The following discussion of existing Army/Navy wave modeling deficiencies is based on operational experience and theoretical considerations. The quantification between model errors and the effect of forcing errors (e.g. wind fields) is not possible at the present.

A. <u>3GWAM - Global and Regional Wave Modeling</u>

Over the past five years, 3GWAM has undergone testing by the Army and Navy wave modeling groups in addition to work originally conducted by the WAM group (e.g. Zambresky, 1989 and Komen et al., 1994). Although not perfect, 3GWAM results generally compare favorable to satellite and in-situ measurements across the worlds oceans, over a variety of synoptic and mesoscale meteorological conditions. Most of these comparisons were based on deep water conditions, and only recently have these extended to shallow water. However, we have documented evidence of situations in which 3GWAM wave estimates need improvement.

a. <u>Deep Water</u>

Both the Army and Navy use the 3GWAM model for deep-water wave predictions. Our experience with mid-size storms (wind speeds between 10-20 m/s) is that the model performs well, but there is evidence that it under-predicts wave heights in large events. Experience, particularly at FNMOC (see Appendix F, and also reported Bender and Leslie, 1994), suggests that the model predictions for long-distance swell requires improvement. Better documentation is required to isolate these model deficiencies that occur in a consistent manner both space and time. In addition to this, a series of statistical tests must be made (e.g. Zambresky, 1989) and posed so that model errors can be isolated from wind field specification errors.

In-house and academic review of this area indicates that although the basis of the model is considered valid, future improvements require a better specification of the individual source terms, in particular, input from the wind and the wave-breaking processes. It is of critical importance to have

1) errors in the specification of the wind fields are substantially reduced so that differences between wave model and measurement can be explained by model deficiencies.
2) high resolution measurements of the wave field and the atmospheric input, as well as the dissipation source be either directly measured or estimated.

b. Intermediate Depth

Both the Army and Navy are using the 3GWAM model for continental shelf, and regional area wave forecasts by increasing the resolution of the grid mesh and activating the shallow water options in the model. Tests of the model in the SWADE (e.g. Cardone et al., 1995) region where the bathymetry is relatively simple indicate that the model has as much skill as it exhibits in deep-water tests in the same region. However, the bathymetry must be significantly smoothed before the model can be run, otherwise it can become unstable. In the past, this problem has been overcome in most all spectral wave models by limiting the gradient in wave energy resulting from large water depth gradients. When the model is applied to new regions, the effect of the smoothing is unknown but can be significant.

The non-linear source term for shallow water is a parameterized version of the deep-water form and has not been independently validated. The need for inclusion of shallow water nonlinear mechanism, such as three gravity wave interacts with on long wave (e.g. edge wave) and non linear dispersion , wave-current effects and depth related breaking should also be considered if this model is to be pushed into very shallow-water regimes. On the shelf, the problem of refraction and shoaling may not be adequately solved with the simplified propagation scheme provided. Additionally, the bottom friction/dissipation mechanism employed in the model is highly empirical. The fact that the model performs reasonably well along the Atlantic mid-coastal region of Duck, NC (location of the Field Research Facility, WES) and the North Sea lies in that the scaling has been empirically corrected for North Sea broad shelf regimes. However, it is not clear how the model might perform under more complicated bottom materials and bathymetric conditions.

c. Propagation Effects/Numerics

3GWAM incorporates two different time steps, one for the solution of the source/sink terms (a time centered implicit scheme) and one for the propagation scheme (first order explicit upstream scheme). For all simulations conducted to date, both time steps have been set to be equal. 3GWAM wave height results appear to be distorted in a north-south, or east-west direction near and in the lee of an offshore island, or at the seaward edge of a cape. This phenomenon was very noticeable in earlier versions of WAM. It was also thought that this problem was remedied by using a higher order numerical scheme. However it is not clear that it has been completely solved. In addition to this, shadow zones caused by island blocking remains unsolved. It may be possible to study this problem with altimetry data presently becoming available from such missions as ERS-1/2 and Topex/Poseidon. There is further problems of whether it is more appropriate to use the energy transport equation or the conservation of action equation.

d. Wind-Wave Growth and Decay

Most time dependent wave models use data from the North Sea Wave Project (JONSWAP) (Hasselmann et al., 1973) as their basis for wind wave growth. This experiment, and subsequent parametric formulations for wind-wave growth were derived for a class of wind speed

conditions of about 10 m/s. Recent work by Kahma and Calkoen (1992) also suggests that the original JONSWAP growth rate expressions were approximately 10-20 percent too low. Stratification of the air-sea temperature data were not observed; thus, frictional velocity scaling of the wind speed may not be consistent. The importance of these findings is that 3GWAM along with all spectral wave models use JONSWAP (or alternate growth rate expressions) as a basis to calibrate the model's capability to estimate growth. If these expressions change, so must the model.

One final point concerns the decay of particular storms. Most of the theoretical work, as well as wave modeling development has concentrated on the proper estimation of the growth sequence. Given symmetric storms (rate of decay similar to the growth stages), 3GWAM performs quite well. When the storm decay rate is faster than the growth, 3GWAM follows a much slower decay rate.

e. Atmospheric Forcing

There are uncertainty limits linked to external forcing functions. For high resolution regional scale, wind fields of similar scale are necessary. Work is presently underway at NRL-Monterey (see Appendix E) that is providing high resolution wind fields on the scales required for wave modeling activities in the regional zone. Systems like NORAPS, and COAMPS are generating high resolution, high quality atmospheric forecasts on a routine basis. An appropriate issue that has not been included (and previously noted) is in the area of temporal variability (e.g. gustiness) and its relative effect on the wave field.

B. **Nearshore Wave Modeling**

Spectral ocean wave models such as 3GWAM are thought to be valid until the water becomes shallow (15 m or so). Ocean waves that have propagated into shallower depths than this generally become increasingly nonlinear. Moreover, shoreward of the 15 m contour of the bathymetry becomes increasingly complex and affecting wave propagation. Several models are currently available for wave prediction in this region: they range from linear to nonlinear, monochromatic to spectral, and time dependent to steady state. For example, the combined refraction-diffraction models such as REF/DIF are often used to predict wave amplitude and direction. Currently nonlinear Boussinesq models appear to offer great potential for nearshore wave predictions. However, these computational requirements make them impractical except for very small regions.

Near the surf zone the bathymetry can change rapidly over short periods of time in response to changing wave and current conditions. At the present time, there is little technical agreement on the most appropriate wave models for making predictions over complex nearshore bathymetry. Significant progress has been made by empirically modeling the breaking of irregular waves which can yield good estimates of wave height over a transect. However, a generalized

spectral model that can produce correct transfers of energy to high and infragravity frequency bands is not available for arbitrary bathymetry, much less for interaction with surf zone currents. Furthermore, the nearshore wave modeling needs to consider the additional new mechanism, such as five wave interactions (Su 1982, and McLean, 1982) three gravity waves interact with one edge wave (Huang and Lin, 1995). The new mechanisms can be many orders of magnitude greater than those three wave interaction (two edge waves with one gravity wave by (Guza and Favis, 1974).

One significant deficiency in the nearshore modeling area is the lack of high resolution (space and time) measurements of wind, waves, water levels, and currents. High resolution directional spectral measurements have been made at the Field Research Facility for nearly 10 years (e.g. Long and Oltman-Shay, 1991). Analysis of this data reveals some of the complexities of this environment, yet at the same time we cannot determine what controls the changes in waves conditions. Large scale field experiments like SuperDuck, Delilah, DUCK 94 (Birkemeier, 1994) and the planning of SandyDuck are steps in the right direction.

C. Summary

The third generation wave model 3GWAM will serve as a basis for global and regional models for the Army and Navy because both services experience suggests that it can meet many of their requirements. This section points out however that although the current model is state-of-the-art, it has some deficiencies in deep water that would be desirable to eliminate. 3GWAM and the suite of other shallow water models have not been proven in shallow water to the same level as 3GWAM in deep water. Considerable technical issues remain for all these models. Most importantly, the level of accuracy suggests that the current technology is inadequate.

III IMPROVEMENT OF WAVE PREDICTION - RESEARCH AND DEVELOPMENT ISSUES

During the four meetings conducted so far by the AN-WPG (June 1994 - February 1995), many diverse issues have been raised concerning improvements of the wave predictions and new developments in the areas of basic research, development, and operations. In order to organize these issues in a more orderly and systematic way, and minimize repetitions as much as possible, we shall present them under ten sections as follows:

(1) Wind field specification
(2) Atmospheric input
(3) Nonlinear wave-wave interactions
(4) Wave dissipation and breaking
(5) Wave-bottom interactions
(6) Wave-current interactions
(7) Nearshore processes and wave transformation
(8) Numerics for wave-current modeling
(9) Wave model verification
(10) Remote sensing, data assimilation and other issues

The above grouping clearly shows the emphasis on wave physics and its modeling schemes. All three levels of research, development and operation, and the three geographical divisions of global, regional and nearshore areas shall be covered simultaneously in each section. When necessary, such levels and divisions shall be specified, otherwise it should be understood that the physical processes and associated modeling are applicable to every level and every division. The logical rational for presenting these issues this way is that much of wave physics is the same in both deep and shallow water. However, due to the additional effects of the bottom, shallow-water waves are subjected to much more complex dynamical processes both in degree and in kinds. Increased naval strategic interest in littoral warfare further underline our focus on nearshore wave predictions.

We shall present section by section these significant issues briefly in this chapter. and leave more detailed presentation in Appendix E-H.

(1) Wind Field Specification

Ocean waves are generated by marine boundary layer wind forcing. So the accuracy of wind field predictions fundamentally limits the accuracy of ocean wave predictions.

The atmospheric and oceanic systems are coupled by boundary layer processes at the interface. Gridded representations of the low-level winds, which are used to drive ocean wave models on a variety of scales, have error characteristics that are influenced

by both observational and analysis errors. Additionally, factors such as the local temporal variability or "gustiness" of the winds may have an important influence on the local generation of waves. Because of the sparse nature of the atmospheric observations over the oceans, often observations are blended with numerical model data to produce winds and surface stress fields over the ocean. Inconsistent horizontal and temporal resolutions between the wave and atmospheric models can lead to significant wave prediction errors. The simulated low-level winds can be very sensitive to atmospheric model parameterizations, such as the planetary boundary layer, surface layer and moist process schemes. The feedbacks between the atmosphere and upper-portion of the ocean are largely ignored in most atmospheric and oceanic model simulations. In some instances, the air-sea interactions may be significant and should be modeled explicitly or parameterized.

In the future, a number of important issues should be considered to improve specification of the low-level wind velocity over the oceans. Numerical model generated data sets need to be created and carefully verified so that accurate surface winds and stresses can be used with confidence for the development and testing of ocean wave models. Analysis and data assimilation techniques need to be improved to increase the accuracy of the wind fields over the oceans. Improvements are needed for the representation of the atmospheric boundary layer and the explicit and implicit interactions of the boundary-layer and the explicit and implicit interactions of the boundary-layer with shallow cumulus convection and stratocumulus clouds. The coupled ocean-atmosphere response to mesoscale forcing needs to be explored further, especially in the coastal zone. Additionally, the surface roughness parameterization of Charnock (1955) should be improved to include the enhanced roughness effects of young ocean waves.

(2) **Atmospheric Input**

We shall first quote from the summary and outlook of WAM Book (Komen et al., 1994):

" The *wind input* term of cycle 4 of the WAM model is based on the quasi-linear theory, which extends Miles' description of shear flow instability. It is in fair agreement with observations both in the laboratory and in the field, although there is considerable scatter in these observations.

It should be realized that the quasi-linear theory is a semi-analytic approximation to the problem of turbulent air-flow over a given wave profile. The full problem of turbulent flow in the coupled air/sea system has not nearly been solved. Only in such a model could one expect to describe realistically such phenomena as air flow separation and the shear in the top layer of the ocean. It is important to compare the present theories in detail with measurements in the boundary layer over growing waves, to see how accurate they are. At the same time one should try to extend the theory."

Janssen (1991), Chalikov and Makin (1991), Synder et al. (1981) and others have developed more detailed models for wind input source term. More discussions on these are made

by Chalikov (1993) and Janssen's reply (1993). All of these models are two-dimensional, that is to say that the wave-growth is in the same direction of the wind direction.

O. M. Phillips is of the opinion that we have gone about as far as we can go with two-dimensional air flow models over sinusoidal waves and calibrated for practical measurement sets that are available, but that we know very little of the effects of the three-dimensionality in the turbulent air flow over short crested waves where non-linearity in the air flow is believed to modify significantly the wind input. Furthermore, the three dimensional wind-wave resonant mechanism discovered by Phillips in 1957 has found some field experimental support (Long, et al., 1994, Young and Banner, 1995, and Banner and Young, 1994). Significantly more experimental work is required. More specifically, in the fetch-limited wave growth condition which occurs frequently in nearshore, off-shore wind situation, the wave direction of peak directional wave spectrum was observed to deviate significantly from the main wind direction, in contrast to all wind input models employed in the present wave prediction models including WAM. Long et al. (1994) proposed that the Phillips resonance mechanism (1957) provides a mechanism for such observation, while Young and Banner (1995) attribute it to nonlinear wave-wave interactions. In principle, the strong three-dimensional wave instability of steep gravity waves (McLean, 1982a, Su, 1982, Su et al., 1982a, Su and Green, 1984, and Su et al., 1982b), which may occur more frequently in fetch-limited conditions, may also contribute to such observations. Hence, the generation of surface waves by wind forcing in fetch-limited stages may no longer be a two-dimensional phenomenon.

Further complication is raised by M. Donelan on the wave decay by the opposing wind that may occur in the turning wind conditions and/or wind forcing on swells propagating in the different direction from the distant sources.

In short, the micro-scale (i.e., the scale of the dominant surface wave length) physics of wind-wave interaction remain in a very uncertain state, and demands urgent basic research and a clearly defined experimental program for improving the wind-wave prediction models.

(3) **Nonlinear wave-wave interactions**

Among the three source terms in the transport equation of wave modeling, the nonlinear wave-wave interaction of weakly nonlinear waves is theoretically described, most adequately by the Hasselman's theory (1962). Unfortunately, the discrete interaction approximation (DIA) of the Hasselman's theory (WAMDI, 1988) gives the directional transfer rate that differs significantly from the exact theory (Komen et al., 1994, p. 485, and Ling, Huang and Pearle, 1994). The authors of WAM group further suggest that it would be useful, therefore, to search for other economic approximation to the Boltzman integral.

Recently, Lin and Huang (1994 a, b) have reformulated the nonlinear wave-wave interaction based on Zakharov's Hamiltonian representation for both deep and shallow water. They found that the directional transfer rates computed from Zakharov and Boltzman

representations are very close to each other, and that the computation time for the former is of one thousand times less than the latter. This faster and accurate computational scheme of Zakharov at the present time is still about 100 to 200 times longer than the rather inaccurate approximation of DIA. Therefore, it is important to search for some schemes to further reduce the computational time of the new scheme probably at the expense of losing some of its accuracy to replace DIA. Lin and Huang (1994c) and Lin et al. (1994) further show theoretically that only four wave (three gravity waves with one long wave instead of four gravity waves) interactions are present in the shallow water, the three gravity wave interactions (Freilich and Guza, 1984 and Resio, 1993) is only an asymptotic approach (Lin and Huang, 1994c).

In the current 3GWAM, the forced non-resonant wave-wave interaction (Herbers and Guza 1994), and the strongly nonlinear three-dimensional wave-wave interaction (McLean, 1982b, Su et al., 1982, and Su and Green, 1984) are not included. The latter three-dimensional interactions are further founded theoretically (McLean, 1982b) and experimentally (Su et al., 1982b) to be more significant in the shallow water than the essentially two-dimensional weakly nonlinear interaction.

(4) **Wave Dissipation and Breaking**

We shall first quote from the WAM Book (Komen et al., 1994, p. 485)

" The section on *deep water dissipation*, shows that much work remains to be done. The WAM model has a wave dissipation source term which is quasi-linear in the spectrum, i.e. linear but with proportionality constants depending on integral spectral properties. Such a source term can be justified under quite general conditions. However, the challenge remains to work out the statistics and hydrodynamics of different whitecapping dissipation theories and to find experimental ways of distinguishing between them. In the end it should be possible to determine the constants from first principles. The same applies *mutatis mutandis* to *dissipation at the bottom*."

Wave breaking has been the most commonly observed wave phenomenon by experts and layman alike, since ancient times. For over a hundred years, it is firmly believed that waves will break when they reach the Stokes' limiting height, which is about 1/7 of the wave length. Since 1960, surface waves of finite height have been found to be unstable and thus change their shapes, and will break even before they reach the Stokes' limit (Benjamin and Feir, 1962) due to the so-called Benjamin-Feir instability, which is a special case of the weakly nonlinear wave-wave interaction described in the last section. This type of wave breaking is essentially two-dimensional. In 1980, Su and his co-workers, discovered a new physical mechanism of wave breaking by steep waves in which an initially uniform two-dimensional steep wave train with wave steepness greater than 0.25 bifurcates into a series of organized three-dimensional crescent-shaped breaking waves that closely resemble those observed in the open sea (Su et al., 1982). The theoretical computation which provide an explanation to these observations was reported by McLean (1982). Later on, Su and Green (1984) further demonstrated experimentally that even an initially low-

steepness (with wave steepness near 0.1) wave train may lead to three-dimensional wave breaking by first going through the Benjamin-Feir instability. In other words, wave breaking may result from a coupling of two essentially different wave instabilities (one in two-dimensional, and other in three-dimensional) of not very steep waves.

Of course, there are other mechanisms that cause waves to break. Phillips and Banner (1974) propose the incident wave breaking in which small waves are prompted to break by the action of longer waves in deep water. The commonly observed wave breaking on the sloping beach is essentially two-dimensional, and is not related to the Benjamin-Feir instability, which is totally suppressed in very shallow water.

When the wind speed is much higher than the phase speed of the surface wave, some different types of wave breaking occur as observed in laboratory wind-wave tunnels, or small waves riding in the trough of much larger waves under storm condition. Several reviews on wave breaking are given by Longuet-Higgins (1988), Peregrine (1983) and Banner and Peregrine (1993).

Besides the loss of momentum and energy (Melville, 1994), breaking process also leads to air entrainment into the water below and generation of bubble clouds (Su et al., 1995). Some of these bubbles will return to the sea surface and burst into small water droplets. These salt-water droplets may be carried upward by turbulent wind and evaporate water in the process to leave behind solid salt particles that form a major portion of marine aerosols. It is worthy to note here that bubble clouds have significant effects on optical and acoustical scattering and that liquid droplets and solid salt particles have strong effects on electromagnetic transmission above the sea surface.

In littoral zones, more wave breaking normally occurs than in deeper water. Of course, the surf zone with or without underwater bars is the area of maximum wave breaking activity even under no wind situations. Swells of distant sources eventually break at the beach with some waves returning to the deep (Elgar et al., 1994). The status of our current limited understanding of the very complex, yet very important aspect of wave breaking, both in deep and shallow water demands urgent basic research consisting of both field measurements and theoretical modeling.

(5) Wave-Bottom Interactions

The wave-bottom interactions, in a real sense, cover every aspect of shallow water waves; some of these have been presented in the previous two sections. Here, we would cover two other aspects that are only significant in shallow water: (a) wave induced transport of sediments in the bottom boundary layer and (b) dissipation of waves by bottom process.

For the aspect of (a), Mei's presentation abstract is included in Appendix E. Mei and Liu (1993) conducted a review on coastal dynamics and surface waves covering diffraction and

refraction, infragravity waves, wave interaction with longshore bars, and oscillating flows over bed ripples.

For the aspect of (b), we quote the abstract of H. Graber's presentation (see Appendix E) as follows:

"Ocean waves propagating from deep to shallow water are modified by the presence of the sea bottom. Wave-bottom interactions impose significant limitations on wave growth which depend on water depth and the topographic composition and features of the sea bed. Few field measurements are available to understand completely the energy balance of waves in finite depth water and the relative importance of depth-dependent processes in the evolution of the wave field. The dominant wave-bottom interaction mechanisms are:

(1) friction from a rough sea bed micro-topography inside a turbulent bottom boundary layer;
(2) percolation in a porous ocean floor;
(3) elastic-type motions of a soft bottom;
(4) scattering on bottom irregularities.

Numerous theoretical, numerical and laboratory studies have been performed to examine various aspects of these dissipative processes on the dynamic and kinematic behavior of ocean waves in finite depth. However, the lack of extensive data sets from field measurement programs limits our understanding over what scales in time and space these processes become evident in the evolution of the directional wave spectrum."

(6) **Wave-Current Interactions**

In the deep water, the effects of strong currents, such as the Gulf Streams and Kuroshio, on the refraction of incoming waves is relatively well-known and theoretically understood except in some special cases such as the frequent occurrence of giant waves in the Agulhas current along the southeast coast of Africa. In the coastal zones, the physical processes become more complicated. The coastal currents may be driven by tides, wind, density variation or river flows. Near the surf zone, intensive wave breaking causes rip currents and longshore currents. Thus, in the nearshore zones, the wave-current interactions are very important for accurate wave predictions.

The transport equation of wave models (such as used in the current WAM) cannot handle the wave-current interactions easily, while it has been known for some years that the wave action formulation can include the current into the wave model (Tolman, 1992 and WAM Book, Komen et al., 1994, p. 47). The trouble with the wave action formulation is associated with its unstable numerical implementation. (Further explanation will be given in the later section on numerics for wave modeling.)

Many shallow water wave transformation models have been developed to compute refraction and diffraction as well as the wave-current interactions. Most of them are based on the linearized mild slope equations with the wave-current interaction terms derived by Dalrymple and Kirby (1983), and Kirby (1984). However, most of the models need more systematic benchmark tests with currents of various directions and magnitudes. The case of horizontally shear current needs further development.

Soulsby et al. (1993) reviewed the wave-current interaction within and outside the bottom boundary layer. An intercomparison of eight typical boundary layer models shows that the general forms of their prediction of mean and maximum bed shear stress were broadly similar. However, variation of maximum stress can be up to 30%. They indicated that the effects of randomness and directionality of waves require more studies.

(7) **Nearshore Processes and Wave Transformations**

Several aspects of nearshore processes have been already presented in the previous sections. Considerable debate is ongoing in the European spectral wave modeling community over whether the spectral ocean models can be taken to the sub-wave-length scale and be improved to include the additional lower number wave-wave interactions or whether this problem must be treated by time domain models of the Boussinesq or Zakharov class which requires information about the phase of the different wave components.

Coupled to the wave problem is the specification of the nearshore bathymetry and currents. Under energetic conditions the wave field can rapidly modify the nearshore bathymetry. It is not clear that is using a highly accurate wave model is justifiable if the bathymetry and current field cannot be adequately specified or predicted.

Given the requirements for accurate wave predictions in this zone it is not clear whether any wave model that is driven from atmospherically driven ocean wave models can meet reasonable accuracy conditions. Models of this zone may need to be driven by up-wave measurements or ocean wave model results that have been significantly injected in measured wave data.

Three other aspects in very shallow water:

(a) transformation of directional wave spectra from the shelf break to the surf zone,
(b) breaking waves within the surf zone, and
(c) numerical modeling of shallow-water waves are discussed in the following:

The aspect (a) is one of the major goals of coastal wave predictions. The physics of this transformation is only partially known at the present and very scant accurate field measurements are available. O'Reilly and Guza have investigated a much simpler related problem

of propagation of swell from the shelf break to the surf zone (see appendix E.)

Most of the wave transformation models are for computation of monochromatic waves. Some recent model developments (e.g., REF/DIF S, Kirby and Ozkan, 1994) include the spectral mode, i.e. propagating waves simultaneously through the domain. Detailed validation of such a model has been hindered by the lack of field data.

As for the aspect (b), we shall quote the abstract of E. Thornton's presentation (see also appendix E);

"Predicting wave height transformation and dynamics in the near shore only requires calculating wave energy quantities, such that simpler first order energetics models may suffice. Predicting sediment transport and morphodynamics requires calculating higher order moments requiring higher order nonlinear models. The order one problem in the surf zone is describing the wave breaking process. Present state-of-the-art models describe breaking waves using a rather crude roller concept (Thornton, 1995).

Verification of wave transformation models within the surf zone may require field data or prototype scale wave flume experiments because of the unknown scaling requirements of the turbulent wave breaking processes. A number of comprehensive field experiments have been conducted which can be used to test models. Also a number of large scale laboratory experiments have been conducted limiting the waves to a single direction. Data required to test nonlinear directional models are the directional spectra across the surf zone, which has not been done to date. Breaking wave processes can be examined using the dynamical integral properties of wave setup and longshore currents."

As for the aspect (c), in addition to the review articles by Mei and Liu (1993) cited earlier, and Hamm et al. (1993), R. A. Dalrymple supplied to AN-WPG a review of numerical modeling of shallow-water waves which is included as Appendix E.

(8) **Numerics for Wave Modeling**

All initial value problems of wave prediction models need to be converted into some types of finite-difference schemes for computer implementation. It is well known that all the finite-difference schemes incur some artificial energy spreading and dissipation beyond the demands of physical processes under consideration. Such energy spreading and dissipation are especially critical, when the numerical schemes require very many time steps and/or over very many spatial grid points. The propagation of ocean swell over a long distance along the earth great circle falls into such a category. It has been pointed out by some investigators including WAM developers that the first-order Euler upstream scheme used in WAM may cause come serious problems of dissipation in swell propagation over long distances, for example in the Southern Hemisphere (Tolman, 1991, Bender et al., 1994, Lin and Huang, 1994a). If the action conservational equation

is applied to the wave model, the wave-current interaction will be easy to include. However, one also has to be careful the Gib instability (unconditional computational instability), such as in Tolman's wave model (1992). Lin and Huang (1994a) have made a critical review of this numerics problem and further developed two better schemes; one for the transport equation and another for wave action equation of wave models. More research on the numerics problem of wave modeling directed at both shallow water and deep water issues is deemed to be quite significant.

(9) **Wave Model Verification**

A key problem with wave models is the need for data to use for validation both for general purposes and in terms of site specific applications. A series of well-documented data sets are needed against which present technology can be benchmarked and model-error characteristics defined. A significant number of these wave data sets already exist and can be rapidly assembled as a benchmark series. However it is necessary to obtain a community wide consensus of which data sets constitute an appropriate benchmark for particular classes of models. Once the benchmark series are available, new models or "improved" versions of older models can be evaluated to quantify the level of improvement. As additional field and laboratory data sets become available they can be added to the set. The data sets should be published and distributed to serve as a community resource.

Army and Navy planners need a world-wide wave, wind and water level climatology. This can be produced synthetically by hindcasts and beginning a program of cataloging nowcasts from forecast centers. This is rather straightforward, but requires updating as models are improved.

Improving the accuracy of predictions in all geographic areas but especially in those areas where we have little experience should motivate programs to measure (remotely or by in situ devices) wave characteristics that can be added to the climatologies or used to validate or calibrate models.

(10) **Remote Sensing, Data Assimilation and Other Issues**

Of course, there are other research and development and operational issues in wave prediction improvements that have not been covered in the previous nine sections. We shall present/discuss some of these in this catch-all section.

One important issue is how to measure directional wave spectra and other wave-related parameters/statistics correctly both in-situ and remotely from aircraft and satellites. These field measurements may be used in several different ways with respect to ocean wave predictions. First, they can be used for tuning any new wave models. Second, they can be used for routine comparisons with predicted data. Finally, they can be assimilated into to the wave prediction model itself in order to increase the accuracy of the wave forecasting. Presently, the great majority

of in-situ wave measurements are provided by moored buoys, notably those 3-m and 10-m NDBC disc buoys. In the future, a series of expandable air-deployed small wave buoys may be deployed in the coastal zone of special Navy/Army interests. For global and regional wave predictions, satellite remote detection employing microwave scatterometers and altimeters of surface wave statistics is obviously more efficient.

R. Peltzer, NRL-DC, provided a detailed overview on waves effect on remote sensing and it is included as appendix H. Much of his observations have been covered in various previous sections with one important exception, i.e., short waves and their implications to microwave remote sensing. Primary microwave backscattering from ocean surface are due to Bragg scattering from short capillary-gravity waves. As such, characteristics and relationship of these short waves to other forcing such as wind speed, longer gravity waves, surfactant, air-sea temperature and so forth are very critical to the ability and quality of satellite ocean wave measurements. In order to utilize satellite remote wave detection as a means for data assimilation in wave prediction models, it may be necessary to fully understand the capillary-gravity waves.

In many coastal areas, the bathymetry may be complex or poorly known. Current fields may be present with the net result that traditional models may never be adequate to make predictions with the required accuracy and reliability. Consideration must be given to techniques that correct these deficiencies by developing hybrid prediction schemes which can combine prediction models with data assimilation.

Considerable theoretical discussions were made in the WAM Book (Komen et al., 1994) about the feasibility of the inverse techniques using satellite wave measurements and WAM predictions for deriving better representations of the dissipation source term. The general idea of such inverse technique is sound, yet it would be workable only if the approximations of physical models on wind wave input and nonlinear wave-wave interactions employed in WAM are sufficiently accurate. It has been described in the previous sections that both of these approximations are rather questionable. Therefore, our present opinion is that it is too early to consider such inverse problems, and that we shall be better off in the near future to strive for better understanding of those physics and corresponding close approximations of the physics.

In concluding this chapter, we would like to make the following remarks. Without question, the 3GWAM is currently the best operationally available wave prediction model. We recognize the considerable contributions of the WAM/SCOR working group in developing this technology and lifting the overall level of wave prediction. We recognize the considerable contributions made by WAM/SCOR group, but our assessment of the state-of-the-art of ocean wave dynamics and its prediction indicated that more work is needed to achieve the level of accuracy required for DoD operations especially in shallow water.

IV. TECHNICAL STRATEGY FOR IMPROVING COASTAL WAVE PREDICTIONS

Review of Army and Navy coastal wave predictions indicate that neither service has a capability to make predictions of the same caliber as in deep water nor at an accuracy level commensurate with service needs. The most significant Army and Navy coastal/littoral operations such as amphibious assault, mine-countermine operations and Logistics Over the Shore operations are very sensitive to surface wave conditions. Prediction errors that are acceptable for most deep water operations are too large for coastal operations. It is likely that existing coastal wave models magnify deep water prediction errors. This is a result of our inadequate understanding of wave generation physics, the lack of good coastal weather predictions, poor knowledge of the bathymetry and bottom characteristics, the sensitivity of wave conditions to currents and water levels coupled with the dynamic nature of near shore bathymetry.

Examination of Army and Navy wave prediction efforts indicate that (1) both services are actively pursuing improvements, and (2) much of the technology needed by one service is directly applicable to the other service. This provides a strong common ground for pursuing joint wave prediction technology. The following strategy is suggested for combining the resources of the Army and Navy and augmenting existing research to implement an integrated prediction system, to develop improved understanding of the wave processes so that the system can be improved, and to develop better connectivity to other models or measurement systems needed to provide boundary or initial conditions or observations for assimilation. The research required to improve predictions also directly feeds other Army and Navy requirements for wave information for other technical needs.

There are three key elements in the proposed plan: (1) developing a state-of-the-art prediction system architecture that can readily incorporate new R&D results; (2) improved understanding of the physical processes related to wave field evolution; and (3) increased data availability and utilization for model validation and calibration. These efforts are described below.

1. Implementation of An Integrated Coastal Wave Prediction System

The Army and Navy have in place many of the components required to construct a first cut coastal wave prediction system. Over the past two years operational and research elements of both services have shared models and assisted each other. Both services are actively performing research in-house and sponsor a significant research effort in academia and industry. We believe these efforts are very promising but there is no clear path for the results to be absorbed into operational predictions systems.

A key element missing in both the Army and Navy research programs is an effort to build a modular wave prediction system that can be readily updated with the new products of the R&D program. The prediction system needs the following components/capabilities.

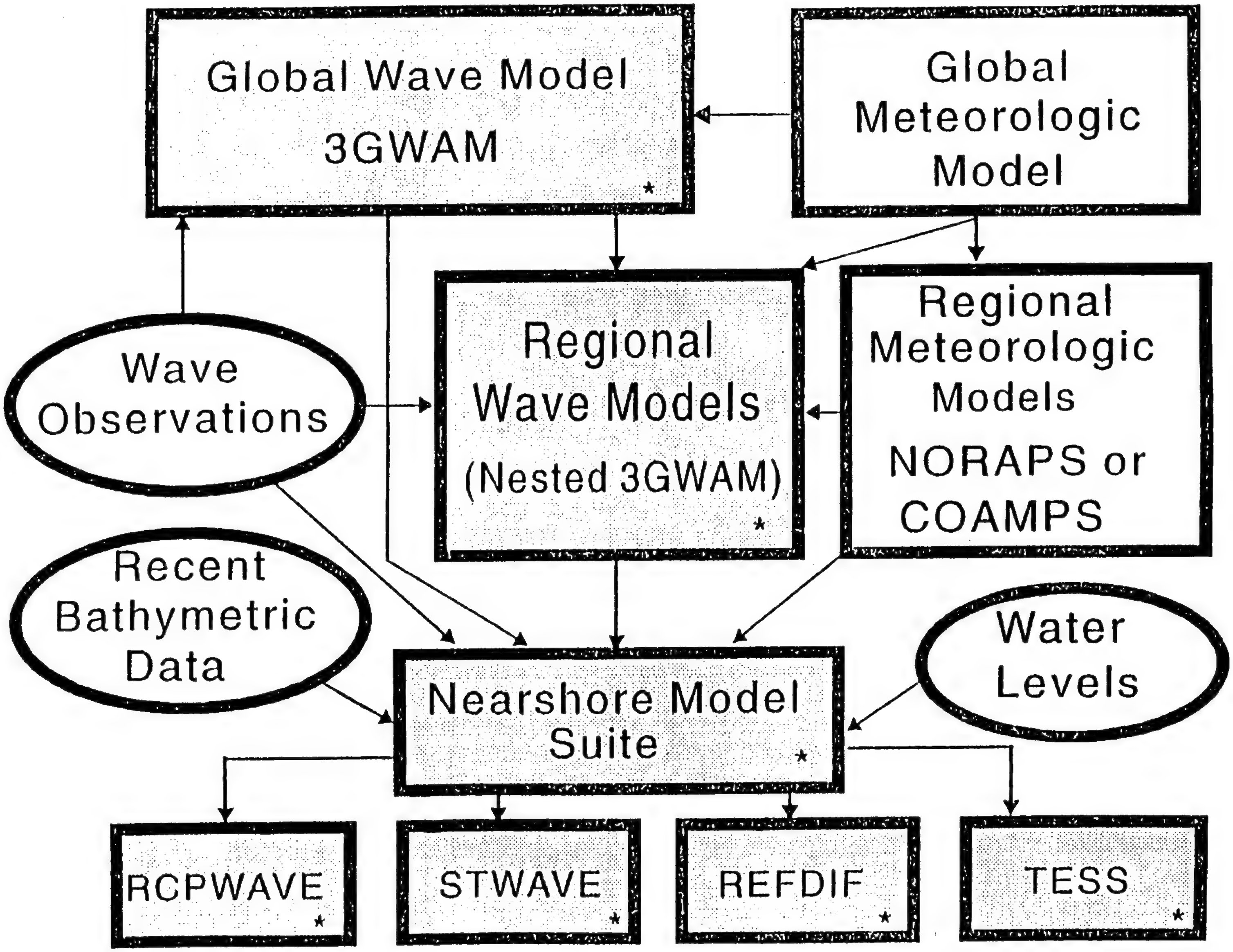
A. Directly interfaced to Navy NOGAPS, NORAPS, COAMPS meteorological models so that best atmospheric forcing can be selected.
B. Capability to nest wave model connections: global, regional/shelf, near shore, inlet and harbor both seamlessly and interchangeably so that for a particular region/operation the best combination of techniques can be combined for the problem at hand.
C. Individual models written in a modular fashion so that new R&D products can be easily incorporated and evaluated.
D. System written to directly interface with standard tide/circulation models and bathymetric data bases so that the system can be implemented rapidly for new areas of interest.
E. System development done with recognition the future need for a higher level of interaction with other oceanographic/meteorological models in truly coupled systems.

The architecture of such a system is conceptualized in Figure 2. using currently available technology. For the case where no observational data are available and the wave predictions are driven by a meteorologic model, waves are predicted using a global wave model driven by the global meteorological model. Wave results are then passed to a regional model which would resolve the bathymetry, coastal geometry better and be driven by a regional wind model (such as NORAPS or COAMPS.) If the situation were particularly complex a nested model approach might be required. Wave data then could be passed to any of a number of nearshore models chosen to be appropriate for the site and driven also be a high resolution wind model such as COAMPS. The nearshore wave models will require inputs of recent bathymetry and accurate water level as well. Of course not all sites would require all levels of modeling. The goal of the system would allow the flexibility to connect the proper combinations of models to tailor the predictions to the site. Another goal of the prediction system would be able to incorporate wave measurements into the predictions.

The overriding goal of this effort is to modularize the forecast model components together so that maximum flexibility is provided to allow the proper combinations of technology to be selected and implemented rapidly. Although the system can run as an integrated algorithm at a major forecast site, the system should be designed so that it can perform distributed processing. For example, the Global forecast might be made at FNMOC, but regional and nearshore components run aboard ship for a specific operation. The practicality of this will advance as data links and computational speeds increase. The potential for this should be designed into the system.

In addition to building a modular system both services need to develop a method for evaluating system performance on a routine basis such as is done for weather models. We also need to develop a series of well documented benchmark data sets so that prospective improvements to the model system can be rigorously tested and level of improvement documented. The model performance evaluation should be coordinated between the operational and research

FIGURE 2



* All wave models can provide output directly to users.

communities in order to gain a clear understanding of where improvements are required.

As part of establishing a continuous improvement program for the prediction system, it is suggested that two or more operational test sites be established where the system's performance can be rigorously evaluated against high quality measured data. Two obvious candidates are the Duck, NC-Camp Lejeune, NC area and the Southern California Bight, because of their operational, training and simulation value and because a baseline measurement capability already exists. Consideration should also be given to develop less costly approaches for developing similar data at other sites of interest or for using remotely sensed data or satellite data if technically feasible.

Review of the deficiencies of present models identified a number of improvements that are relatively straightforward developmental efforts. These include improving the nonlinear interaction source term in the 3GWAM model by including more wave components, increasing the accuracy of the swell propagation routine in the 3GWAM model and improve the shallow water propagation routines in the 3GWAM. These changes could be made at the same time the models were modularized.

2. Improving The Understanding of Coastal Wave Physics

Our review of state-of-the-art coastal models indicated that many of the processes are represented in a highly empirical or parameterized fashion. The technical experts felt that good results were more likely to be a result of tuning to specific conditions than due to firm understanding of the physics. The goal of a research effort should be to replace the empirical aspects of models with algorithms that had more physics and fewer adjustable constants. The in-house and academic technical panels recommended R&D on many individual research items that have significant merit. The following were judged to be the most important issues to be addressed. Some of these issues are currently being studied; however, a significant need is to provide a more direct pathway for incorporating these into the prediction system and evaluating the result.

Coastal meteorology/air-sea interaction

Coupling COAMPS model with coastal wave and circulation models
Coupling wave and mixed layer models

Wind input to waves

Rate of wind input as function of wind direction
Improved input function including Phillips' resonance mechanism
Rate of wind input in the presence of swell

Nonlinear transfers of wave energy in the wave field

Confirmation of the Hasselmann source term in shallow water

Formulation of Zakharov equation (Resio and Perie, 1991) for deep water and shallow water nonlinear transfers for four wave and three wave interactions
Transfers of energy to infragravity waves
Effects of currents on nonlinear source functions

Wave breaking

Quantification of whitecapping/development of white capping source term
Wave breaking in shallow water
Wave breaking on currents

Wave propagation

Refraction/shoaling/diffraction by bathymetry and currents (including long shore, rip currents)
Reformulation of model into action density

Bottom dissipation

Bottom friction and boundary layer mechanisms
Percolation
Various bottom types

Waves/shore/bathymetry coupling

Three dimensional swash run-up
Beach morphology evolution: bar and trough movement
Nearshore current prediction

These areas of research involve theory and measurements of the phenomena in the laboratory and field. In particular, the technical panel emphasized the significant need for high resolution, scientific measurements of wave field evolution over shoaling depths and the surf zone at the same time that the pertinent physical processes are measured so that the appropriate balance between the processes can be deduced. These measurements are needed over a range of wave and weather conditions and in a variety of physical settings. Experiments at more than one site are needed.

In the past, research on these topics has largely emphasized an analysis of the individual process in isolation from all others. Wave evolution models typically incorporate the simultaneous action of a sum of many such individual processes. In order to obtain a satisfactory prediction scheme, these processes must be balanced with each other. We suggest that high quality field measurements are needed to quantify these individual processes and can serve as a mechanism for

focussing the R&D efforts on improvement of wave evolution and transformation models. Rather than a series of independent single field studies, the research should focus on a sequence of field studies in differing conditions/settings where several of the relevant processes are measured at the same time. We feel that the synergism could produce a marked elevation of the state of the art in wave prediction. These field studies should look at wave evolution from deep water through shoaling depths to the surf zone and should include a range of meteorological conditions. Studies are also needed in areas with very irregular bathymetry and areas with very different bottom materials. We emphasize that our call for systematic experiments are our attempt to focus fundamental investigations toward resolution of a critical problem and are not a call to replace or stop fundamental studies.

3. Coastal Data Collection Needs

The coastal/littoral wave prediction problem is inherently more difficult than the deep water problem because of the increased complexity and number of source/sink terms in the balance equation and due to the complexity of wave propagation over shallow depths. The geologic materials that constitute the shelf and beach floor may well have significant impact on the wave prediction problem by altering the relative role of dissipation. Time dependent currents and the mobility of the bathymetry likewise introduce uncertainties that are unlikely ever to be resolved from a pure physics approach. It was the conclusion of many of the scientists involved in this analysis that extensive data sets will be required in areas of critical importance so that the prediction system may be checked or calibrated to adjust for the uncertainties described above in order to achieve the level of accuracy needed.

The potential data needs are quite diverse. The spatial variation of the wave field must be measured to verify the modeled transformation of waves from an 'outside' boundary to a point of interest. Data for many nearshore areas may be needed in order to validate the model over a range of weather and flow conditions. Although directional spectra are of primary interest, less detailed information may also be of use. Many approaches are available for gathering the data and there is no particular requirement on the sensor system other than its accuracy and limitations be understood. The use of the data can range from climatological data for planning, to event specific data for model calibration, to real time data for assimilation or forcing of the models. Indeed, in simple wave transformation cases (not strongly dependent on local wind) a variety of simplified approaches may be of possible use to Army/Navy operations.

We also recognize that remote sensing offers the possibility of providing great spatial detail over wide areas where other wave information is lacking. We suggest that some research be directed at how site specific sequence of this data collected at different times can be combined with modeling and statistical optimization techniques in order to produce hybrid prediction schemes which combine the advantages of observational platforms and sophisticated model technology to improve predictive skills.

Often time circumstance can make applications of more complicated observation and prediction technology impossible, inefficient and more simple approaches can be implemented

prediction technology impossible, inefficient and more simple approaches can be implemented effectively. The final goal of the Army-Navy Wave Group is to improve wave prediction. An appropriate approach is to provide a number of such techniques that can be interfaced with the global and regional data and predictions routinely made available.

Clearly the injection of data into the prediction system may well be as important to successful predictions as any other factor. Coupling data with a physically correct prediction model may be the optimal approach to improving predictions for the near term in coastal waters given the complexity of the wave growth and decay process and the potentially extreme variation of bathymetry, water levels and currents in the littoral region.

V. Summary

Our review shows that the Army and Navy lack the wave prediction capabilities with the accuracy necessary for coastal/littoral operations. Existing coastal models are thought to amplify deep water wave prediction errors that are provided as boundary conditions and which are too large in any case for many critical coastal/littoral operations. We have shown that the Army and Navy have sufficient common ground that can serve as a basis for a joint prediction system that can meet the needs of both services and have identified research and development activities required to achieve this objective.

Our recommendations are that the Army and Navy build a prediction system that meets operational needs and perform critical fundamental research to reduce the empiricism in many of the source/sink terms incorporated in the model. This system should be built in a modular architecture and should be designed so that research products can be easily absorbed and the prediction system improved. We suggest that the R&D efforts seeking improved wave physics be focussed about a series of coastal field experiments to enhance the transfer of understanding directly to the models. An effective mechanism for this is the formulation of a series of critical field experiments that pull together the major research components with the goal of understanding the evolution of the wave field for different meteorological and geophysical settings. We have made these our primary recommendations because there is not currently a systematic approach for bringing the new R&D products into an operational model.

We also emphasize the high value of wave data to a prediction system. Significant efforts should be made to increase the provision of wind and wave data for use in making predictions. Even small amounts of data in a region where a wave prediction system has not been checked may provide significant feedback into the quality of the predictions. By coupling the wave process and wave model research efforts with R&D on data assimilation and fusion, the potential exists to produce a hybrid prediction system may be better than one driven purely by atmospheric forcing. The strategy we suggest offers approaches for the short term by development of a modular approach to an improved prediction system. However, the second component of the program is the long term strategy of coupling fundamental process studies together through a series of multi process field studies. We recognize that fundamental studied are a long term instrument but believe that the synergy of coupling them together with modeling will have short and intermediate term payoffs in improved predictions as the physics is sorted out. In coastal and littoral regions where bathymetry and currents are highly complex, a combination of models driven by data may be the only way to provide the accuracies needed.

Appendix A: AN-WPG Members and Additional Meeting Participants

Provided ~~b~~below is a current list containing the Army/Navy Wave Prediction Group Members.

U.S. Army Corps of Engineers Waterways Experiment Station

C. Linwood Vincent
Robert Jensen
Donald Resio
Zeki Demiribelk
Jon Hubertz
Carolyn Holmes
Martin Miller

Naval Research Laboratory - Stennis Space Center

Ming-Yang Su
Larry Hsu
John Harding
Casey Church
Albert Green
Sunny Breeding
Jim Kaihatu

Naval Research Laboratory - Monterey

Simon Chang
Jim Doyle

Naval Research Laboratory - Washington DC

Rodney Peltzer

Naval Oceanographic Office

Andy Johnson
Paul Farrar

Fleet Numerical Meteorology and Oceanography Center

Paul Wittmann
Linda Zambresky

Provided below is a current list containing additional participants of various Army/Navy Wave Prediction Group meetings.

Office of Naval Research

Tom Kinder
Bob Peloquin
Joe McCaffery

U.S. Army Corps of Engineers Waterways Experiment Station

David McGehee
Jane Smith
Ed Thompson
H. Lee Butler

Naval Research Laboratory - Stennis Space Center

Tim Keen
Mike Stanley
Dennis Lundberg
George Kerr
Jim Lewis
Rick Allard

National Data Buoy Center

Ken Steele
David Wang

Univ. Del.

T. Dalrymple
J. Kirby

Oceanweather

V. Cardone

Neptune Sciences

M. Earle

MIT

C.C. Mei

RSMAS/ Univ. of Miami

H.C. Graber

NASA/GSFC

N. Huang

R.-Q. Lin

SIO
R.T. Guza
W.K. Melville
J.W. Miles
Bill O'Reilly

PMEL/NOAA
J. Overland

Naval Postgraduate School
E. Thornton
Thomas Herbers

Washington State Univ.
Steve Elgar

CCIW
Mark Donelan

Appendix B: Army and Navy Wave-Related projects

(1) Navy Wave-Related Projects
   a. High-resolution optical sensing in littoral zones with a UUV (bubble density) Co-PI: M. Su, FY 95-96
   b. Directional wave spectrum and void fraction measurement within Littoral Optical Environment. Co-PI: M. Su, FY 95-96
   c. Characterization of bubbles distribution in littoral zones. PI: M. Su, FY 97-99
   d. Optical signature in littoral zones (effects of waves, foams, bubbles). Co-PI: M. Su, FY 96-99
   e. Coastal aerosol modelling (marine aerosol generation). Co-PI: M. Su, FY 97-99
   f. Coastal sensor fusion (task four - surface waves). PI: J. Boyd, FY 95-99
   g. Coastal Scene Description. PI: G. Heburn and T. Keen, FY 95-99
   h. Coastal Wind Forecasting: J. Doyle, S. Chang
   i. Wave Modeling: Andy Johnson, Paul Farrar
   j. Navy Operational Wave forecasting: Paul Wittman
   k. Coastal Simulation. PI: Jim Kaihatu, FY 95-99
   l. Surf Model Upgrade, PI: L. Hsu FY 96-98

(2) Army Wave-related projects
   a. Coastal Field Data Collection Program Gaging Program
   b. Wave Information Studies
   c. Modeling Evaluation of Wave Spectra in Shallow Water
   d. Development of a New Generation Finite Element Harbor Model
   e. World Wave Climatology for Logistics Over the Shore
   f. LOTS Wave Forecasting System
   g. Directionality of Waves in Shallow Water

(3) a. ONR Waves BAA, FY94-96
   b. ONR Littoral Wave Mechanics, FY97-01. Program managers are Tom Kinder, Lou Goodman, Tom Curtin, Frank Herr, Dennis Trizna, Scott Sandgathe, and Joseph Kravitz

Appendix C

HARBOR WAVE MODEL ASSESSMENT

Zeki Demirbilek/WES, Larry Hsu/NRL-SSC, Andy Johnson/NAVOCEANO

INTRODUCTION

Harbors may be considered the terminating points for waves emanating from deep water transforming through the regional and nearshore waters. In peace and war times, both the Army and Navy have specific military missions planned worldwide either in the vicinity or inside friendly and hostile harbors and ports. Successful planning and execution of these missions requires detailed knowledge of the waves. Additional needs for harbor wave prediction include:

- ship routing
- ship berthing
- dredging in harbors
- recreational and commercial boating and fishing
- harbor resonances
- navigational hazards
- coastal engineering applications

The main objectives of Army/Navy harbor modeling development are: (a) develop a fully elliptic, accurate and reliable wave model for large harbors of arbitrary shape; (b) customize the new harbor model for possible onboard utilization on medium-size computers, and (c) provide a generalized and flexible harbor model for possible integration with other hydrodynamic and atmospheric models. The harbor wave model should include the following processes: wave refraction, diffraction (by bathymetry, structures, islands, etc.), reflection, dissipation (by friction and breaking), nonlinear amplitude and frequency dispersion, and effects of both the irregular coastlines and currents (tidal or other surface currents) on short and long waves.

STATUS

The Elliptic mild-slope wave equation (MSE), also known as the combined refraction-diffraction equation (CRD), is now a well accepted method for estimating waves in seas. The Corps of Engineer's HARBD model is based on theoretical developments from early 1970's by Mei (see Chen and Mei, 1974). The WES version of the HARBD model has been revised to include the short period waves; it has been used for several harbor projects in Hawaii in the 1990's. HARBD predictions often do not compare favorably with the physical model studies, and it may not be appropriate to improve this model since it demands excessive computer resources. For example, it is not possible to use HARBD for moderate and large size harbors even on super Crays (i.e., more than 20,000 nodes). Due to these drawbacks of the MSE, in the 1980's we have seen the development of several simplified models based on the so-called parabolic approximation. The parabolic approximation considers only the forward propagation (i.e., no reflections), and weak lateral scattering by assuming a primary propagation direction centered around the incident carrier wave. For the open coast applications, the parabolic approximation based wave models usually

provide good estimates of the integral wave parameters (height, period, direction). These models are used with rectangular grids, background currents are assumed not too strong and bathymetric variations are mild. Parabolic models may be less reliable when used in coastal areas where diffraction and scattering effects are important (i.e., wave reflection, backward scattering). Since the full elliptic MSE models account for these important processes, these models should in principle be better suited for wave modeling in the harbors and nearshore.

The US Army Corps of Engineers Waterways Experiment Station has initiated in FY 95 a research work unit toward developing a new generation finite element harbor model to ultimately replace the HARBD model. The main goal of the effort is to provide a more efficient model that has fewer limitations compared to HARBD. A joint Navy/Army research for wave modeling in harbors should expand the scope of WES's new initiative, and attempt to provide a set of different types of harbor wave models. Both the steady and time-dependent models based on the MSE, Green-Naghdi, Boussinesq, and Volume of Fluid approaches should be considered in the joint effort. The practicality issue associated with the time-dependent models could be a significant barrier, but some features of the time-dependent models may be useful for harbor applications.

Recent advances in the finite element computational algorithms have overcome several known numerical difficulties of the elliptic MSE models, and these models may now be used more easily for engineering applications (Panchang et al., 1990, 1991). NAVOCEANO and NRL-SSC are presently participating with WES to evaluate the capabilities of a harbor model developed by Prof. V. Panchang, University of Maine.

DEFICIENCIES

Existing harbor wave models have a number of deficiencies as follows:

a. Incorporate additional processes: Existing harbor modeling technology is unable to include combined effects of the wave amplitude nonlinearities, wave breaking, and wave-current interaction in the simulations.

b. Treatment of boundary conditions: The treatment of the open (offshore) boundary conditions remains an unsolved problem for mild-slope and Boussinesq type of wave models. The open boundary problem (i.e., radiation boundary condition) in the MSE is further complicated by the requirement that the adjacent coastline be fully reflective and that the open sea outside the model area to be of constant depth. The waves reflected by the offshore coastlines into the open seas intercept with the incident waves in the exterior domain, giving rise to a wave field that does not represent the actual wave climate necessary to excite a harbor. The assumption that the downwave coastlines have to be straight vertical boundaries (i.e., vertical wall boundary) may not be appropriate for oblique incident waves.

c. Restrictions on harbor geometries: There are restrictions on the type of harbor geometries the present model can analyze. Harbors with multiple entries cannot be modeled with the existing harbor wave models because these geometries require modeling very large domains,

exceeding the capacity of the available computational resources. Multiple-connected harbor domains are also not amenable to the present theoretical formulations. Mathematical treatment of the multiple-entry harbors requires further research.

d. Frictional losses: Existing harbor modeling formulations neglect both the friction losses due to seabed and harbor entrances. The effects of these losses may be important for some wave periods and harbors subjected to swells in the Pacific Ocean. The information required for representation of the frictional losses may be site-specific and rarely known. These losses cannot be easily deduced from physical model studies due to scaling effects. Both theoretical and experimental studies are needed to quantify the frictional losses occurring in the harbor entrances.

e. Reflection and transmission coefficients: Existing harbor model predictions show a high sensitivity to the specified (input) values of boundary reflection coefficients. Predictions change drastically if these coefficients are varied. The lack of information and guidance for selecting these coefficients is part of the problem. Look-up tables, derived from field and laboratory data, may be necessary to ensure proper values are used during modeling. A great deal of research is needed for studying an impedance condition for oblique wave incidence on beaches an structures. Research should be directed at determination of the reflection and transmission from both impermeable and porous structures under normal incidence and oblique wave attack. Wave transmission through permeable breakwaters should be further studied for harbors. Water wave propagation in jettied channels should also be investigated since some harbors are preceded by structured jetties.

f. Sensitivity to characteristics of the offshore region: The water depth as well as the size of exterior region both strongly influence the wave estimates inside a harbor. Different results may be obtained by simply increasing the size of the exterior domain or if the value of depth in the deep water region is changed. Note also that the HARBD model does not allow water depth in the exterior domain to vary; it must be a constant. This is unrealistic because in typical applications the bathymetry in the exterior region is quite variable. Alternatives to the semi-circle representation of the offshore region of the harbor geometry should be theoretically explored. Different descriptions of the infinite domain outside the semi-circle should be studied (i.e., parabolic modeling in the infinite region) to minimize boundary contamination that occurs offshore.

g. Coupling with circulation models: Existing harbor models are often used in a stand-alone mode and coupling to the circulation (tidal) models and other wave models is not a feasible option. To properly include effects of water level variations and tidal currents on the wave predictions in the harbors, it is necessary to couple harbor models with the circulation models.

h. More efficient numerical solvers: The numerical solution techniques used in the existing harbor models prohibit modeling the large size harbors. The largest harbor to date analyzed with HARBD had less than 15,000 finite element triangular nodes. This resolution is inadequate since short waves usually require 6 to 15 nodes per wavelength for elements 20 feet in size. These requirements restrict the modeling domain to approximately 1 square-mile area. Computationally very efficient numerical models are necessary for modeling moderate and large

harbors. Higher-order triangulation of the geometry may be necessary to better resolve the nonlinearities in extreme shallow depths.

i. Wave nonlinearities: Present models for wave effects in harbors are designed for linear, monochromatic waves. There is need to incorporate effects of the wave amplitude nonlinearities. Wave trains with multiple frequencies and directions are prohibitively expensive to model with the existing models. Harbor models should have capabilities for both regular and irregular waves for investigating effects of multi-frequency and multi-directionality.

j. Infra-gravity waves: Harbors with sufficient opening to the seas may also be influenced by the long-wave energy penetrating into such harbors. Okihiro et al. (1995) investigated the harbor seiche by coupling a nonlinear model for infragravity wave generation outside the harbor with a linear harbor seiche amplification model. Harbors in the Pacific Ocean where waves periods in the infra-gravity range (30 sec to 500 sec) are frequently seen due to earthquakes and tsunamis.

k. Data deficiency: Both ideal and real harbor configurations should be tested in the development and validation of the new harbor modeling technology. Comparison with other models may be done, although other models should not be used as benchmark; field measurements must be considered as the benchmark for model evaluation and acceptance. Validation tests should make use of both laboratory and field measurements available worldwide, and these tests should not be limited to a few harbors in the Pacific Ocean.

In summary, research needs are dictated by the above described deficiencies. These can be lumped into two main categories, short- and long-term needs:

Short-term needs:

- improvement of the present technology for immediate operational needs using newer FE algorithms and BC's,
- development of new capabilities which do not exist in the present technology (effects of wave frequency and amplitude nonlinearities, wave breaking and dissipation, sea bed and entrance induced frictional losses, wave-current interaction, and spectral predictions),
- systematic validation with laboratory and field measurements,
- GUI capabilities for grid generation and pre- and post-processing,

Long-term needs:

- integration with other wave and circulation models,
- pursue alternative formulations (Green-Naghdi, Boussinesq, BEM, VOF),
- to develop a wave theory for harbors of arbitrary geometry and variable depth that includes the combined effects of short waves riding on the long waves,
- other long-term research topics as discussed above.

Appendix D

Current and Future Atmospheric Modeling Capability

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Currently, on the regional scales, the Navy Operational Regional Analysis and Prediction System (NORAPS) (Hodur, 1987) is run operationally for 4-5 regions with a horizontal resolution of 20-45 km. In this version of NORAPS, the boundary layer parameterization makes use of a level 2.5 closure technique with explicit equations for the turbulent kinetic energy and turbulent dissipation. This sophisticated treatment of the turbulent transport enables more accurate 10 m winds and surface stress to be predicted than previously possible with level 2.0 closure methods. The fluxes of heat, momentum and moisture at the air-sea interface are parameterized based on surface-layer similarity theory following Louis et al. (1982). A nested version of NORAPS is currently being transitioned to operational status with 45 km grid increment on the outer mesh and 15 km on the inner mesh. This nested version of NORAPS will run for several select regions. A data assimilation and analysis cycle for moisture will be implemented in the near future.

The Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) has nonhydrostatic atmospheric dynamics that solves the fully compressible equations of motion valid for a wide range of scales of motion that encompass the micro- to synoptic scales (Hodur, 1993). COAMPS is currently being applied in a research and development mode. Real-data simulations with horizontal resolutions ranging from 1 km to 10 km are being tested and verified. This triply-nested model is capable of simulating a variety of mesoscale phenomena including land/sea breeze circulations, atmospheric convective systems, topographically forced flows, coastally driven circulations, tropical and extra tropical cyclones and fronts. In regions of complex mesoscale forcing where kinematic analysis is often difficult due to sparse data, COAMPS is capable of simulating fine-scale structures with greater accuracy than static analysis techniques. The boundary layer is parameterized in COAMPS using a level 2.5 closure method following Deardorf (1980) and Therry and LaCarrere (1983). In this scheme, the mixing and dissipation length scales are parameterized separately. Surface similarity theory is used to parameterize the heat, momentum and moisture fluxes (Louis et al., 1982). A Charnock (1955) formulation is used to compute the roughness length over bodies of water. In the future, higher-order closure boundary-layer schemes will be tested. Operational implementation of the atmospheric portion of COAMPS is planned for Summer 1996. The horizontal grid increment will be 5-9 km on the fine mesh for regions of interest. Currently, COAMPS can be run in support of field studies and special cases of interest in a research and development mode at horizontal grid increments of 2-5 km.

COAMPS has been coupled to the Wave Model (WAM) (Doyle, 1995) following the work of Janssen et al. (1989) and Janssen (1991) and a hydrostatic mesoscale ocean circulation model

(Hodur, 1993) in research and development modes. The development of a coupled mesoscale modeling system is a challenging problem, and operational implementation of such a system is at least several years into the future. The ultimate goal is to have an operational coupled mesoscale ocean-atmosphere data assimilation and prediction system with mutually interactive ocean circulation, ocean wave and nonhydrostatic atmospheric components. Because of the complex nature of the coupled problem, a great deal more work is needed before the interactions of the mesoscale ocean-atmosphere system can be simulated in an operational environment.

The Navy Operational Global Atmosphere Prediction System (NOGAPS) (Hogan et al., 1991) is presently run operational twice daily at a T159 (about 80 km) horizontal resolution with 18 vertical levels. Future improvements to NOGAPS will include increased horizontal (÷50 km) and vertical (36 levels) resolution and an improved boundary layer scheme. NOGAPS is coupled to a ocean mixed-layer model in a research and development mode and an ocean circulation component is currently being tested and developed. Satellite data assimilated into NORAPS, COAMPS and NOGAPS include SSM/I winds, TOVS and DMSP sounding data, SSMI precipitable water, cloud track winds and MCSST data. Other observations that are assimilated include fixed and drifting buoys, aircraft, ship and conventional surface and upper-air observations. In the future, scatterometer data from ERS-1 as well as water vapor winds and SSM/I precipitation will be added to the data assimilation system.

The atmospheric and oceanic systems are coupled by boundary layer processes at the interface. Surface winds over the sea are a crucial component of this air-sea coupled system. Gridded representations of the low-level winds, which are used to drive ocean wave models on a variety of scales, have error characteristics that are influenced by several factors. Observational errors limit the reliability of gridded analyses created by objective and subjective methods. Wu (1995) compared wind speeds from buoy measurements, ship observations, and model-based analyses using satellite-altimeter returns. He concluded that these wind speeds from buoys and ships must be used with caution because large, systematic deviations were found. Additionally, observations over the sea are sparse and typically only representative of local conditions. Objective analysis schemes can spread the influence of these observations hundreds of kilometers, which may be justified at times and inappropriate for other conditions. A direct comparison of the analysis and observational data is not always a good indicator of the accuracy of the analysis because of these representativeness questions. Yet, the definition of the wind field is critical to the success of a good wave forecast. A 10% bias in the 10-m wind speed (not an uncommon error) can be manifested as a 10-20% error in the significant wave height and a 20-50% error in wave energy (Komen et al., 1994).

Additionally, factors such as the local temporal variability or "gustiness" of the winds may have an important influence on the interfacial fluxes and therefore, the local generation of waves. A series of wind records at a given location may be characterized by the same mean wind speed but have different magnitudes of gustiness. One way of characterizing the turbulence level is by dividing the root-mean-squared (rms) deviation from the mean by the mean wind speed. This fraction can reach values of up to 20-30% according to Monahan and Armendariz (1971) and Sethuraman (1979). A 30% gustiness level can lead to an increase in significant wave height of

more than 30% (Cavaleri and Burgers, 1992).

Unfortunately, describing gustiness as an rms about a mean cannot adequately describe the characteristics of wind variability. A detailed analysis of a wind record reveals that sequential values have a strong correlation only over a short period of time. Wind time series with identical levels of rms errors from the mean but different correlations between sequential wind values have been shown to introduce additional large oscillations in the significant wave height (Cavaleri and Burgers, 1992). Current operational wave models do not account for wind variability and typically assume the wind is constant over a 3 hour interval.

Because of the sparse nature of the atmospheric observations over the oceans, often these observations are blended with a model simulation to produce winds and surface stress fields over the ocean. Thus, the numerical atmospheric model is an important component of the generation of surface winds that are ingested by ocean wave models. The horizontal resolution of the atmospheric model determines the scales of motion that are resolvable. Wave and atmospheric models should share a consistent resolution. The momentum transport to the sea surface takes place on turbulent scales and needs to be realistically parameterized. Mesoscale phenomena that may have an important influence on the low-level wind fields are typically not well represented in global analyses. This is especially true in the coastal environment where large contrasts may exist between the land and sea in surface transport and topography. For example, surface wind fields generated by a global model may lack potentially important mesoscale information such as land/sea breezes, low-level jets and coastally driven disturbances. Temporal resolution of the wind field data need to be specified with a great deal of care as well. For wave model applications with coarse horizontal resolution, relative sparse temporal resolution may be sufficient. However, for smaller spatial scales, where mesoscale winds may vary over relatively short time scales, temporal resolution on the order of 1 h may be required to resolve the translation and evolution of these phenomena.

The atmospheric model parameterizations of physical processes may have important deleterious effects on the low-level winds. The representation of the planetary boundary layer is generally handled through subgrid scale correlation terms since the model grid resolution is too coarse to explicitly resolve the turbulent eddies and fluxes. Atmospheric models typically make use of similarity theory to parameterize the surface layer. Many of the parameterizations have been developed and tested using data in steady state and homogeneous conditions. In storm conditions with high winds and large transport of heat and moisture between the air and sea, the boundary layer parameterizations can be crucial in determining the mesoscale response to the oceanic forcing. However, in these situations the parameterizations of the planetary boundary layer have been infrequently validated due to lack of observations. Also, in stably stratified boundary layers, the turbulent transport is difficult to accurately parameterized. Because of computational expense, simplifications are often made in the parameterizations, especially in the global models. For example, in NOGAPS, a first order closure parameterization is used while COAMPS and NORAPS both make use of the more sophisticated 1.5 order closure method.

The feedbacks between the lower atmosphere and upper-portion of the ocean are largely

ignored in most atmospheric and oceanic model simulations. In some instances, the air-sea interactions may be significant and should be modeled explicitly or parameterized. Nearly all atmospheric models use the Charnock (1955) relationship to represent the influence of the sea state on the roughness of the surface. However, it has been shown that this parameterization may significantly underestimate the roughness length in the presence of young ocean waves. The relationship does not consider the wave age or directional spectrum. As a result, the low-level winds and mesoscale structure may be impacted, as well as the kinetic-energy dissipation rate even for synoptic scales (Doyle, 1995). Additionally, the feedbacks associated with the heat and moisture transport between the ocean and atmosphere may influence the atmospheric stability in the low-levels. As a result, the vertical mixing of momentum can influence the surface wind velocity.

In future studies, a number of important issues need to be considered that effect the specification of low-level wind velocity over the oceans. Numerical model generated data sets need to be created and carefully verified so that accurate surface winds and stresses can be used with confidence for the development and testing of ocean wave models. Data sets from field studies that have increased temporal and spatial resolution observations over the oceans need to be exploited. With these accurate, high temporal- and spatial-resolution data sets, the impact of errors in the wind field can be assessed as well as the benefits of higher spatial and temporal resolution wind velocity information. These data sets should include both storm and quiescent conditions, as well as cases in which the wave models did not perform adequately.

Analysis and data assimilation techniques need to be improved to increase the accuracy of the wind fields over the oceans. New techniques should be developed that will ingest remotely-sensed high temporal- and spatial-resolution data from a variety of data sources with differing error characteristics and data densities such as data from satellites, Doppler radars and wind profiling systems into a dynamically-consistent data set. The analysis and data assimilation problem is particularly complex in the coastal zone where marked contrasts often exist in the low-level surface forcing as well as the atmospheric boundary layer. Adjoint methods, nudging procedures, assimilation using optimal interpolation, and normal model initialization need to be tested in the coastal environment where contrasts in the land and sea forcing can be used to improve the accuracy of the data assimilation and ultimately the low-level wind velocities.

Improvements are needed for the parameterization of the atmospheric boundary layer. Higher order closure methods should be explored to improved the parameterization of the subgrid scale transports. Baroclinic and stable atmospheric boundary layers need to be simulated with greater accuracy. The response of the boundary layer to heterogeneous surface conditions, often present in the coastal zone, needs to be parameterized more accurately. Information concerning the turbulence and gustiness needs to be incorporated into the wave models. Additionally, the explicit and implicit interactions of the boundary-layer with shallow cumulus convection and stratocumulus clouds should be represented.

The air-sea exchange process must be explored further, especially in the coastal zone. The exchange of heat, moisture, momentum and particulates between the sea and air is an important

component in the ocean-atmosphere system, especially in the coastal zone. The fluxes can be particularly important in determining the coupled ocean-atmosphere response in the coastal environment. Coupled responses are often more pronounced in the coastal zone where spatial and temporal scales in the ocean and atmosphere are similar. Young ocean waves can have a marked effect on the boundary layer momentum flux, which can influence the atmospheric stability and vertical transport. Recent studies by Janssen et al. (1989) and Janssen (1991) suggest that the effect of wind-generated ocean waves can have an important influence upon the wind stress in the surface layer because the wave-induced stress is a considerable fraction of the total stress (Komen, 1985). These effects can feedback to the ocean wave generation, which in turn may influence the boundary layer structure. The coupled ocean-atmosphere response to mesoscale forcing needs to be explored further. Additionally, the surface roughness parameterization of Charnock (1955) should be improved to include the enhanced roughness effects of young ocean waves. The sensitivity of ocean wave prediction to the wind energy input as a function of the relative angles of the wind direction and to the wave frequency-directional spectrum needs to be investigated. Furthermore, research in determining the critical height at which the wind interacts with waves is needed, especially in high wave conditions, in order to assess the necessary degree of detail in specifying the surface layer vertical wind profile. In summary, a collaborative effort needs to be established between the atmospheric and wave modelers to evaluate, verify and improve the low-level wind velocity simulation and prediction as well as to begin to unravel the intricacies of the mesoscale air-sea interaction problem.

Appendix E: Abstracts of Presentations at the 4th AN-WPG Meeting at Monterey, CA, Jan. 31 - Feb. 2, 1995

Oceanic Scale Marine Surface Wind Field Specification

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Abstract:

Recent hindcast studies will be reviewed which strongly suggest that surface marine wind fields may be analyzed sufficiently accurately in oceanic mid-latitude extra tropical regimes such that wind errors do not mask errors in wave models. The same studies, however, indicate that despite remaining uncertainties in source terms, contemporary wave models provide sufficient accuracy for most practical purposes provide they are forced by accurate surface winds. The requisite wind field accuracy has been achieved to date only through direct (objective or subjective) analysis of the surface windfield (kinematic analysis) and only in regions occupied by operational measurement arrays comprised of buoys and/or platforms separated typically by no more than about 200 km (e.g. North Sea, Western North Atlantic and Eastern North Pacific). Extension of this level of skill globally involves mainly resource issues, not resolution of major technological or scientific questions. For example, the existing buoy arrays could be simply expanded or an operational multi-satellite scatterometer remote sensing network deployed based upon present instrument capabilities, with the measured wind data assimilated routinely into objective or interactive objective kinematic analysis (KA) systems implemented at National Weather Prediction (NWP) centers.

The accuracy of forecast marine surface wind fields is mainly dependent on accuracy of numerical atmospheric forecasts in general. Most contemporary NWP models include marine boundary layer formulations and numerics which translate model forecast skill of the 3-D structure of the atmosphere into marine surface winds with little bias. The most important deficiency of NWP models in relation to errors in wave forecasts, in addition to the inevitable error growth with time to the chaotic limit (typically one week), is the resolution of small-synoptic scale features in forecast wind fields. Particularly important features include flow discontinuities, accelerated flows near fronts, and propagating jet streaks. However, recent studies of marine cyclogenesis and evolution in which mesoscale models are coupled to ordinary global NWP models, suggest that many such features may be resolved routinely in the forecast domain even without significant initialization of such small features in the initial state.

Mesoscale and Coastal Meteorology

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Abstract:

Often the highest observed waves are associated with mesoscale weather phenomena imbedded in larger scale weather systems. Here mesoscale is defined by the range of 50-300 km. Three examples are given, polar lows, squall lines, and coastal jets. Often smaller secondary storms can develop in a low-level baroclinic zone near the center of a mature occluded large scale low pressure system, the so-called poisonous tail of an occluded front. An example of a polar low from the North Pacific had a 38 m/s boundary layer wind and increased the significant wave height to 13.5 m, from a background height of 10 m, the highest recorded NDBC report for that period. Squall lines are narrow, rapidly moving lines of thunderstorms. These features can resonantly force shallow-water gravity waves that steepen and break at the shore. An example of these longer period waves is shown from the east coast of Florida, but similar features occur in the Great Lakes and Gulf of Mexico. Forcing of coastal winds occurs from contrasts of heating, orography, and friction along a coastline. The mass and windfield simultaneously adjust to this change over a seaward extent of a Rossby radius of deformation, $LR=NH/f$, where N is the stratification, H is the height of the disturbance and f is the Coriolis parameter. H can be mountain height, buoyancy height, or inversion height. For typical values, $LR \sim 50\text{-}100$ km. Within this region, winds can accelerate ageostrophically, parallel to the coast giving an increase in speed and change of direction relative to offshore winds. An example of such a case of a coastal jet is shown for Southeast Alaska where the most hazardous seas occurred after the passage of the front. Along the Carolina coast the continental shelf oceanic front can provide a region for increased wind convergence and storm generation.

Wind-Wave Energy Transfer: Theory

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Abstract:

The linear theory of energy transfer from a turbulent wind to a surface wave is reviewed. The quasi-laminar model (Miles, 1957) is modified to incorporate the wave-induced perturbation Reynolds stresses (neglected in the quasi-laminar model) through a viscoelastic model based on Townsend's boundary-layer evolution equation. **Preliminary** calculations suggest that these Reynolds stresses may reduce the energy transfer for $c < 10U_*$ (c = wave speed, U_* = friction speed of logarithmic profile) and may render the energy transfer negative in some neighborhood of $c = 5U_*$. These results differ from those for an eddy-viscosity (Boussinesq) model, for which the energy transfer is enhanced by the Reynolds stresses and remains positive for all c, and may be anomalous.

Experiments Concerning the Growth and Attenuation of Waves by Wind

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Abstract:

A series of laboratory experiments were conducted to explore various aspects of the wind-wave interaction process. The experiments were of three types in which the phase velocity of the waves was in turn: a) zero, b) directed against the wind, and c) directed with the wind.

In series (a) measurements were made of the pressure on wavy walls of various steepness ($ak = 0.079, 0.157$ and 0.314), and with the surface roughened to various degrees to produce aerodynamically smooth, transitional and rough flows. Equivalent sheltering coefficients for the fully rough case were within a factor of two of the growth rates of field and laboratory cases.

In series (b) mechanical waves were generated by a hinged paddle at the downwind end of a 100 m tank. The pressure on the surface of both monochromatic and random waves indicates substantial direct attenuation by the wind and this is borne out by the spatial gradient of wave energy. In series © the paddle waves were generated in the wind direction and the measurements repeated. In this case the equivalent coefficients were roughly 50 % larger than those of series (b).

The effect of wave breaking on the enhancement of the growth rate was explored using wavelet analysis to identify time dependent phase shifts linked to incidence and intensity of breaking. It appears that mild breaking does indeed increase the phase shift, but pronounced breaking reduces the pressure amplitude so that the effect of the increased phase shift is nullified for the most intense and correspondingly rare breakers. On balance the effect of breaking on the growth rate is substantial.

Finally, the effect of paddle waves on the stress is explored. The long waves may dominate the stress under appropriate forcing conditions, and they also have significant dynamic and kinematic effects on the short waves - themselves stress receptors. Taken all together the complexities of the wind-wave interaction process stand in sharp contrast to the usual prescription used in numerical wave prediction models. We have indeed come a long way since the subject was given a substantial impetus in the fifties (Miles, 1957; Phillips, 1957), but wind-wave interaction is

far from a solved problem. Perhaps the greatest need now is for field experiments designed to explore these and other facets of wind-wave interaction. With reliable field and laboratory data, the use of non-stationary analysis may well point the way to new theoretical and numerical approaches in the near future.

Progress Report on the Goddard Coastal Wave Model

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Abstract:

A new coastal wave model is being developed at Goddard Space Flight Center, which will eventually be used as part of the coupled wind-wave-current coastal dynamics modeling. The Goddard Coastal Wave Model (GCWAM) is based on the action conservation law for the propagation side of the model equation, in which the full nonlinear dispersion was also included. We have developed a second order implicit scheme was developed for the propagation terms. On the source function side, the nonlinear wave-wave interaction source term has been totally re-formulated based on Zakharov Hamiltonian representation extended to shallow water. The results are drastically different from the one generated by DIA used in WAM. Additionally, we have examined some high quality wind wave directional spectral development data, and concluded that the wind input source function also needs to be examined critically.

Dissipation by Breaking Waves

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Abstract:

Of the processes contributing to the evolution of ocean surface waves, dissipation, primarily due to breaking, is the least understood. Current operational numerical models of dissipation in the radiative transfer equation are based either on heuristic physical arguments or hypotheses of equilibrium from which the dissipation is indirectly determined. This is in contrast to the models of wave generation and nonlinear interaction which are based on rational theories. At present we have neither the theoretical nor observational tools to make direct predictions or measurements of dissipation as a function of surface wave number as is required in the theoretical framework; however, recent progress is encouraging. Observations of enhanced dissipation in the wave zone have been shown to be consistent with laboratory measurements of breaking waves, and with a simple turbulence model balancing dissipation with vertical transport of turbulent kinetic energy. Laboratory and field measurements have demonstrated the importance of acoustics for tracking and quantifying breaking, including correlations between dissipation, air entrainment and the radiated sound. Microwave techniques have also begun to prove useful in identifying and tracking breaking waves. Developments in high frequency acoustic Doppler instruments hold the promise of more routine measurements of breaking and turbulence in the surface wave zone. These advances and future research directions will be presented.

Wave-Induced Transport of Sediments in and Below the Bottom Boundary Layer

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Abstract:

Based on our past works on granular flows, oscillatory flows over rigid ripples, and diffusion of suspended particles in wave boundary layers, we sketch current research on the transport of sediments either in suspension or as bed-load. In the former we are focussing on the formation and migration of ripples, and the attendant transport of sand and the formation of sand bars. In the second we are focussing on the large-scale spreading of very fine silt in various wave patterns dictated by coastline topography. The main items are:

1. Ripple formation and migration in progressive waves on an initially plane bed.

2. Ripples migrating on bars in partially standing waves on an initially plane bed.

3. The effect of an obstacle on the ripple migration in waves.

4. Extension of our dispersion theory in wave boundary layers, by modifying models of eddy diffusivity and bottom boundary condition. Examples will include the spreading of sediment cloud near a coastal island.

While much of our work will be theoretical, laboratory experiments are also planned to guide as well as verify the theory.

Dissipation of Ocean Waves Over the Shelf by Bottom Processes

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Abstract:

Ocean waves propagating from deep to shallow water are modified by the presence of the sea bottom. Wave-bottom interactions impose significant limitations on wave growth which depend on water depth and the topographic composition and features of the sea bed. Few field measurements are available to understand completely the energy balance of waves in finite depth water and the relative importance of depth-dependent processes in the evolution of the wave field. An overview of different wave-bottom interaction mechanisms and their relative strengths and effects will be presented. The dominant mechanisms are:

1. friction from a rough sea bed micro-topography inside a turbulent bottom boundary layer;

2. percolation in a porous ocean floor;

3. elastic-type motions of a soft bottom;

4. scattering on bottom irregularities.

Numerous theoretical, numerical and laboratory studies have been performed to examine various aspects of these dissipative processes on the dynamic and kinematic behavior of ocean waves in finite depth. However, the lack of extensive data sets from field measurement programs limits our understanding over what scales in time and space these processes become evident in the evolution of the directional wave spectrum.

Breaking Waves within the Surf Zone

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Abstract:

Wave transformation models within the surf zone are reviewed in terms of requirements for particular applications, present capabilities and future needs. The various models may be classified as probability density, spectral, stochastic, deterministic, nonlinear and time domain. Model requirements vary with application. Predicting wave height transformation and dynamics in the near shore only requires calculating wave energy quantities, such that simpler first order energetics models may suffice. Predicting sediment transport and morphodynamics requires calculating higher order moments requiring higher order nonlinear models. The order one problem in the surf zone is describing the wave breaking process. Present state-of-the-art models describe breaking waves using a rather crude roller concept.

The various research modeling efforts underway are reviewed. U.S. efforts include Naval Postgraduate School, Scripps, University of Delaware, Northwest Research Consultants, CERC. A large European effort is being funded under the Mast program and the Japanese have an active research program.

Verification of wave transformation models within the surf zone may require field data or prototype scale wave flume experiments because of the unknown scaling requirements of the turbulent wave breaking processes. A number of comprehensive field experiments have been conducted which can be used to test models. Also a number of large scale laboratory experiments have been conducted limiting the waves to a single direction. Data required to test nonlinear directional models is the directional spectra across the surf zone, which has not been done to date. Breaking wave processes can be examined using the dynamical integral properties of wave set-up and longshore currents. Verification of models is examined and future needs discussed.

Propagation of Swell from the Shelf-break to the Surf Zone

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Abstract:

Wave-generation (by wind) and wave-dissipation (by wave breaking) are often important processes in the evolution of surface gravity waves. Here we consider situations in which generation and dissipation can be neglected. The specific locale considered is Southern California, where the coastal wave field is often dominated by long period swell waves generated by distant storms in the Southern Hemisphere or the Gulf of Alaska. Wave energy radiating from storms propagates along great circle routes and in the deep ocean decays very slowly with distance. Although propagation of swell (outside the generation region) over distances of a few 100km is relatively straightforward in the deep ocean, the effects of complex offshore bathymetry (e.g. islands and banks) can result in strong spatial inhomogeneity of the coastal wave field. In the Southern California Bight, wave energy can vary by an order of magnitude between sites separated by only a few km. Remotely generated waves, strongly modified by complex bathymetry, might also be important to the regional wave climate in Hawaii, the Phillippines and other island chains.

Promising model-data comparisons are shown. The linear and dissipation-free models, which include the effects of island sheltering and refraction, are initialized with observations of the directional wave field seaward of the Channel Islands which border the southern California mainland. Model predictions are compared to extensive observations inshore of the islands near the mainland coast. The potential for forecasts as well as nowcasts, and the possibility of using coastal observations to improve the estimates of the deep ocean directional spectrum, are discussed.

Nonlinear Wave Interactions in Shallow Coastal Waters

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Abstract:

Nonlinear wave-wave interactions are important to the evolution of wind-wave spectra, the generation of sea floor microseisms, the interpretation of remote sensing data, and nearshore fluid and sediment processes. Nonlinear wave effects in the ocean are usually modeled with a stochastic, weakly nonlinear theory based on a perturbation expansion for small wave steepness (e.g. Hasselmann, 1962). This theory predicts forced secondary waves excited in non-resonant triad interactions with two wind-wave components, and free tertiary waves resulting from resonant quartet interactions.

In shallow coastal waters, nonlinear triad interactions are near-resonant and the associated forced secondary waves are strongly amplified. Of particular interest are difference-frequency interactions involving two swell components which are believed to cause energetic low-frequency motions (so-called 'surf beats' or 'infragravity waves') commonly observed near shore. Whereas second-order nonlinear wave effects are readily detectable in observations, the effects of tertiary waves, in particular the importance of resonant quartet interactions to the evolution of wave spectra across a broad shallow continental shelf, are less understood.

Finite depth nonlinear perturbation expansions break down in very shallow water and do not accurately predict the shoaling evolution of waves on beaches. Various models for shoaling waves have been developed based on the weakly dispersive Boussinesq equations for varying depth (e.g. Peregrine, 1967) that allow for resonant triad interactions, but this approach has not been extended yet to stochastic, directionally spread incident waves.

Ongoing field measurement- and modeling efforts focused on nonlinear wave-wave interactions on the continental shelf and beach (nominal depths 1-200 m) are discussed.

Numerical Modeling of Water Waves — Some Models and Some Problems

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Abstract:

In the past 15 years, the modeling of water waves has improved tremendously. Phenomena not fully treated in the past have been included in models, such as diffraction and spectral effects, and the growth of computing power on the desktop and the speed of supercomputers have permitted models to be built that could not have been in the past. In addition to the new modeling technologies, a lot of hard work has provided unprecedented field and lab data for comparisons of models.

In this presentation, I will review some of the recent progress in wave modeling and types of models that are available and then talk about problem areas that still need solutions.

Appendix F.

OPERATIONAL WAVE FORECASTING AT FLEET NUMERICAL METEOROLOGY AND OCEANOGRAPHY CENTER

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1. INTRODUCTION

The U.S. Navy's Fleet Numerical Meteorology and Oceanography Center is the Department of Defense central production site for all standard fully-automated real-time meteorological and oceanographic prediction products (Plante, 1995). Fleet Numerical fulfills this role through a suite of sophisticated global and regional meteorological and atmospheric models, extending from the top of the atmosphere to the bottom of the ocean (see Plante and Clancy, 1994). The Third Generation Wave Model (WAM; WAMDI Group, 1988) is an integral and important part of this model suite, providing twice-daily ocean wave forecasts to a variety of customers from both global and regional implementations.

2. GLOBAL WAVE MODEL

The Global WAM (GWAM) became operational in May of 1994, replacing the first-generation Global Spectral Ocean Wave Model (GSOWM), which had been operational at Fleet Numerical since 1985 (see Clancy *et al.*, 1986). The replacement of GSOWM with WAM was part of a larger transition at Fleet Numerical in which an obsolete Cyber 205 computer was replaced by a state-of-the-art Cray Y-MP C90 as the primary production platform at the center (see Plante and Clancy, 1994).

GWAM is forced by surface wind stresses provided by the Navy Operational Global Atmospheric Prediction System (NOGAPS), the Fleet Numerical global numerical weather prediction model (see Hogan and Rosmond, 1991). GWAM runs in a fully automated fashion, making two "ontime" and two "offtime" runs per day keyed to the four-per-day NOGAPS run cycle. The two ontime runs produce wave forecasts to forecast times of 144 hours from 0000 GMT and 1200 GMT. The two offtime runs are initialized from the 6-hour forecasts of directional wave energy spectra produced by the previous ontime run and valid at either 0600 GMT or 1800 GMT. The offtime runs integrate the model's energy spectra forward in time 6 hours (to either 1200 GMT or 0000 GMT) using forecast wind stresses from the corresponding NOGAPS offtime run (see Bayler and Lewit, 1992). These spectra become the initial conditions for the following ontime run, thus maintaining continuity.

The GWAM runs on a 1° spherical grid, with directional wave energy spectra resolved into 24 directions and 25 frequencies. A weekly updated northern and southern ice edge is applied to suppress waves under the ice. The input wind stress fields are available at three-hour intervals, but are interpolated to a one-hour wind forcing time step. The wave propagation time step is 20 minutes. Output fields are produced every 6 hours into the forecast, and include significant wave height, maximum wave height, sea height, swell height, mean wave period and direction, peak wave period and direction, sea period and direction, swell period and direction, and white cap probability. Directional wave energy spectra are also output every 12 hours into the forecast and available as a random access data base at each model grid node to support ship routing and other applications. All GWAM output is managed via the Integrated Stored Information System (ISIS) data base management system (see Copeland and Plante, 1994).

3. REGIONAL WAVE MODELS

WAM was first applied operationally at Fleet Numerical as a regional model for the Mediterranean, becoming operational on the Cyber 205 in July of 1990 (see Clancy and Wittmann, 1990). This initial regional

implementation of WAM replaced the first-generationMediterranean Spectral Ocean Wave Model (MSOWM), which had been operational at Fleet Numerical since the early 1970s.

The current regional implementations of WAM run on the Cray Y-MP C90 and are forced by the Navy Operational Regional Atmospheric Prediction System (NORAPS), the Fleet Numerical regional numerical weather prediction model (see Hodur, 1987). All of the regional WAM models run in a fully automated fashion, making two ontime runs per day to conform to the twice-per-day NORAPS run cycle. Thus, continuity is maintained by initiating the models with the 12-hour forecast directional wave energy spectra from the previous (12-hour old) ontime run.

The Mediterranean regional WAM (MEDWAM) and the Indian Ocean regional WAM (IOWAM) have grid resolutions of 0.25° latitude/longitude, while the Korean WAM (KORWAM) has a grid resolution of 0.20°. IOWAM and KORWAM obtain open boundary conditions for directional wave energy spectra from GWAM. All three of the regional WAM implementations run with shallow water physics to include the effects of bottom friction and wave refraction (see WAMDI Group, 1988). In addition, all three output the same fields as GWAM to ISIS at every 6 hours into the forecast.

A summary of the Fleet Numerical WAM implementations is given in Table 1.

4. VERIFICATION

Verification of GWAM is done on a routine basis by comparing predicted wave heights, peak periods and wind speeds to those observed by moored buoys. Standard error statistics are computed on a monthly basis and published in the Fleet Numerical Quarterly Performance Summary Report. Figures 1 and 2, based on verification of 6-hour forecast model fields produced by both ontime and offtime runs against data from buoys in the Gulf of Alaska during January 1995, show typical results.

As indicated by the dashed least-squares line on the scatter plot of Figure 1, GWAM shows a tendency to <u>overpredict</u> wave heights in the low wave-height range and <u>underpredict</u> wave heights in the high wave-height range. This tendency is likely a result of the fact that GWAM is run in only a one-way coupled implementation with NOGAPS. That is, GWAM is forced by the wind stress predicted by NOGAPS, but

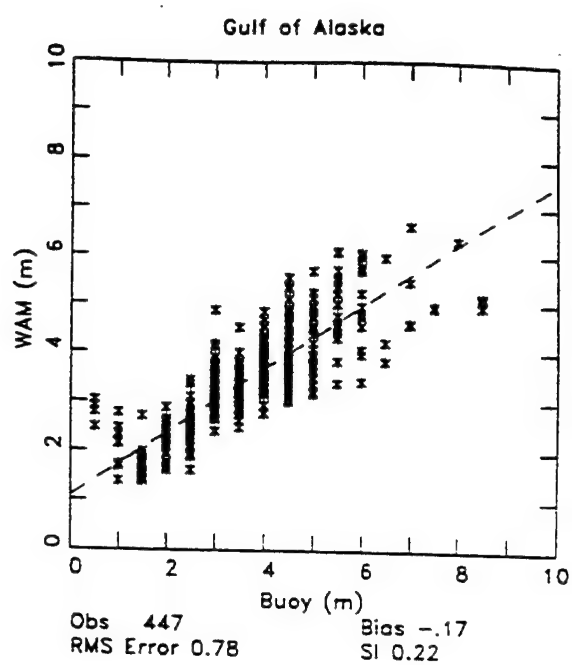

Fig. 1. Scatter plot of significant wave heights predicted by GWAM (6-hour forecasts produced by the ontime and offtime runs and valid at either 0000, 0600, 1200, or 1800 GMT) versus significant wave heights observed at buoys 46001, 46003, 46036 and 46184 in the Gulf of Alaska during January 1995.

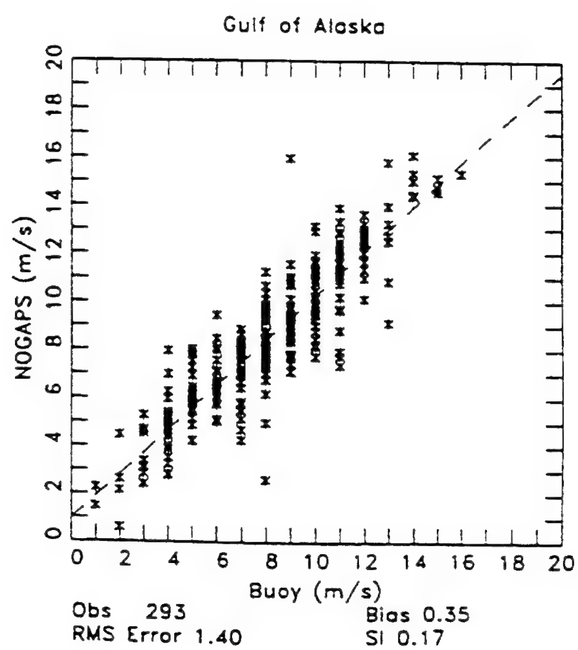

Fig. 2. Same as Fig. 1 but for wind speeds at 10 m height predicted by NOGAPS and wind speeds observed at 10 m height by the buoys.

TABLE 1
FLEET NUMERICAL WAM IMPLEMENTATIONS

	GWAM	IOWAM	MEDWAM	KORWAM
Forecast Time	144	48	72	36
Shallow Water	NO	YES	YES	YES
Wind Forcing	NOGAPS	NORAPS	NORAPS	NORAPS
Nesting	N/A	YES	NO	YES
Latitude Range	90S-90N	0-28N	28N-45N	28N-53N
Longitude Range	0-359E	42E-100E	10W-39.75E	110E-143E
Grid Resolution	1.0°	0.25°	0.25°	0.2°
Model Time Step	20 min	15 min	15 min	10 min
Wind Time Step	3 hours	3 hours	3 hours	3 hours
Ontime Forecast	0600(00Z)	0630(00Z)	0530(00Z)	0630(00Z)
Completion Time	1800(12Z)	1830(12Z)	1730(12Z)	1830(12Z)

the NOGAPS wind stress calculation is unaffected by the surface roughness implied by the wave-height field predicted by GWAM. This is in marked contrast to the two-way coupled implementation of WAM advocated by Janssen (1994).

In any case, the root-mean-square (RMS) wave height error (0.78 m) is quite good for wintertime conditions and substantially better than that reported by Clancy *et al.* (1986) for GSOWM in this region during January 1985 (i.e., 1.27 m). In addition, the scatter index parameter, defined as the standard deviation of the difference between the predicted and observed fields divided by the mean of the observed field, is also quite good. The GWAM scatter index in the Gulf of Alaska for January 1995 (0.22) is substantially less than the corresponding GSOWM scatter index in the Gulf of Alaska for January 1985 (0.35; see Clancy *et al.*, 1986).

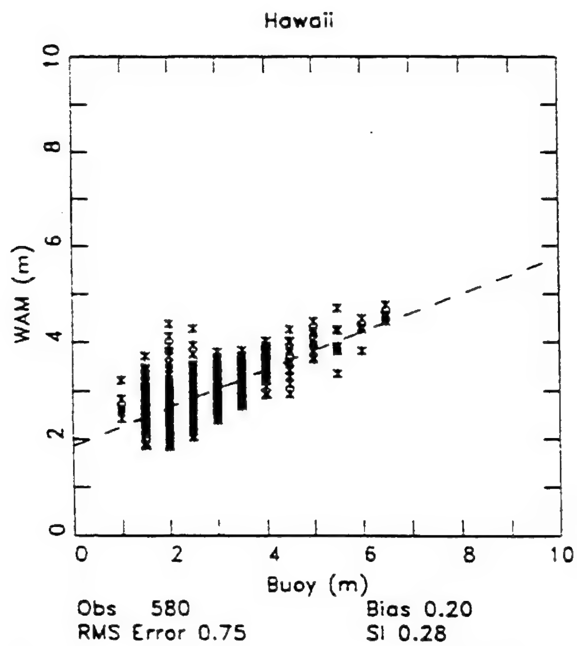

Fig. 3. Scatter plot of significant wave heights predicted by GWAM (6-hour forecasts produced by the ontime and offtime runs and valid at either 0000, 0600, 1200, or 1800 GMT) versus significant wave heights observed at buoys 51001, 51002, 51003, 51004, 51026 and 51027 near Hawaii during January 1995.

Of course the improvements in wave prediction skill indicated above are due, in part, to improvements in the accuracy of the winds that drive the wave models. As demonstrated by Figure 2, the NOGAPS 10 m winds were quite good in the Gulf of Alaska during January 1995, showing a low scatter index (0.17) and only a slight tendency to overpredict low wind-speed events and underpredict high wind-speed events.

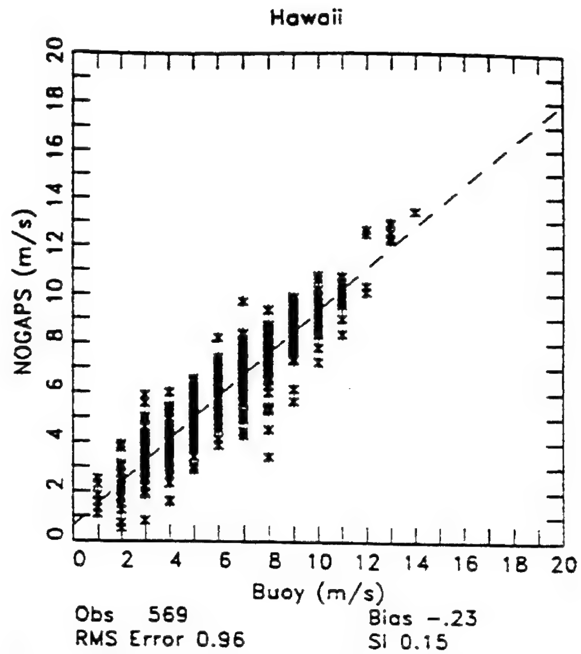

Fig. 4. Same as Fig. 3 but for wind speeds at 10 m height predicted by NOGAPS and wind speeds observed at 10 m height by the buoys.

GWAM has a more marked tendency to underpredict high wave events in swell-dominated regions than in areas dominated by windsea. Figures 3 and 4 show comparisons of wave and wind predictions with buoy observations near the Hawaiian Islands. The NOGAPS winds show only a small negative bias here (-0.23 m s^{-1}), while the GWAM wave height shows a negative bias at the upper wave height ranges. A closer look at the wind and wave record at buoy 51001 (Figure 5) indicates an underprediction of swell events, which originate from storms in the north Pacific. This model tendency is consistent with that found by Zambresky (1989). See Wittmann and Clancy (1993) for further verification of Fleet Numerical wind and wave predictions with buoy data.

Monthly trends in the mean and RMS errors for GWAM and NOGAPS can be seen from Figures 6(a) though 6(d). The monthly RMS errors increase with forecast time for both winds and waves. The RMS errors increase during the northern hemisphere winter, of course, because of increased atmospheric variability. The mean errors for the waves are slightly positive and increase with forecast time, while the mean errors for the winds are sightly negative for a forecast time of zero, and also increase and become positive with forecast time.

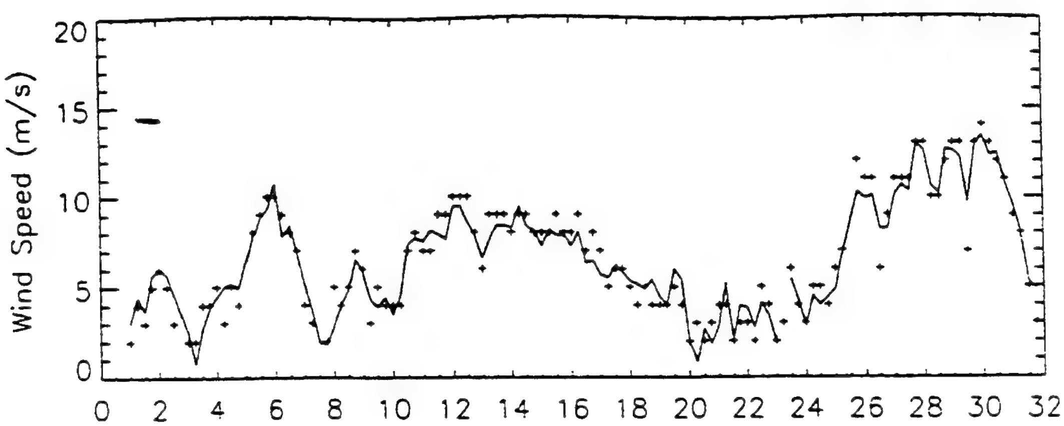

Fig. 5(a). Observed (crosses) and predicted (solid line) wind speed at 10 m height at buoy 51001 near Hawaii during January 1995. Predictions are from the NOGAPS analysis (i.e., for a forecast time of zero hours).

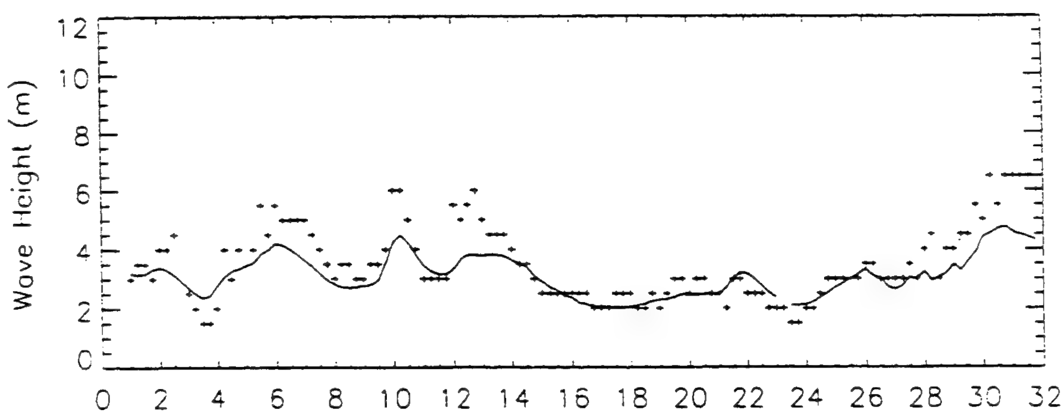

Fig. 5(b). Same as 5(a) but for significant wave height observed by the buoy and predicted by GWAM

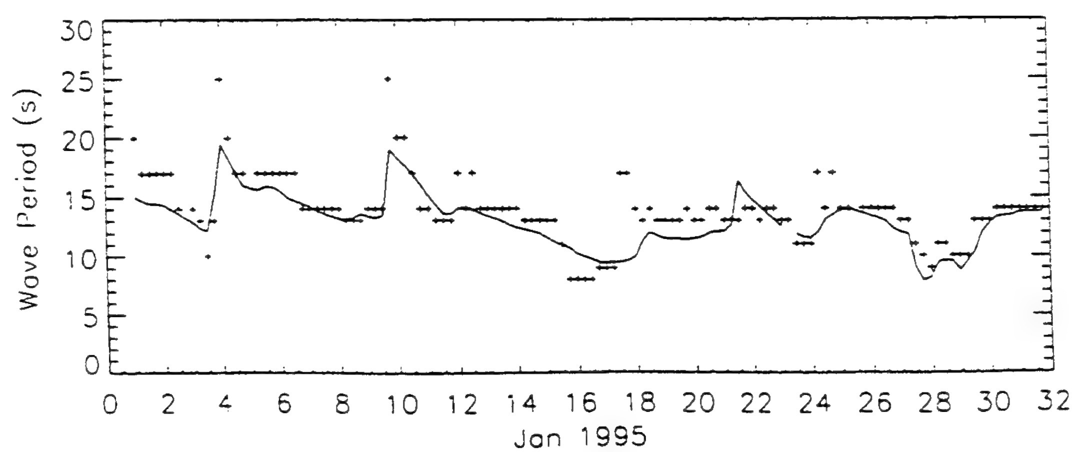

Fig. 5(c). Same as 5(a) but for peak wave period observed by the buoy and predicted by GWAM.

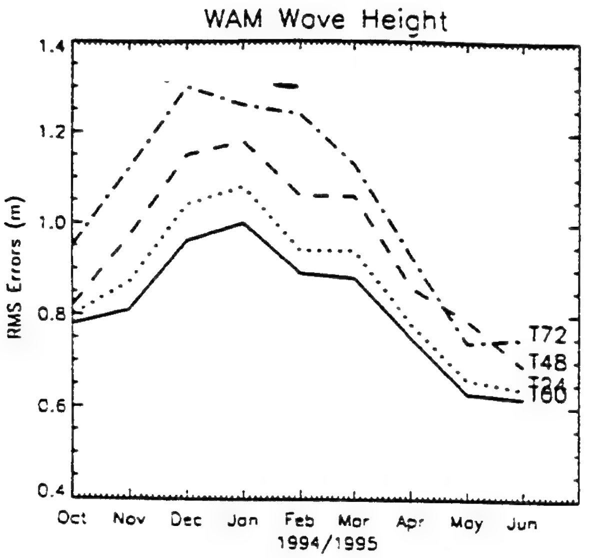

Fig. 6(a). Monthly averaged RMS significant wave height errors for GWAM for forecast times of 0 (solid), 24 (dotted), 48 (dashed) and 72 (dash-dot) hours based on comparison with all available moored buoy data in the North Atlantic and North Pacific from October 1994 through June 1995.

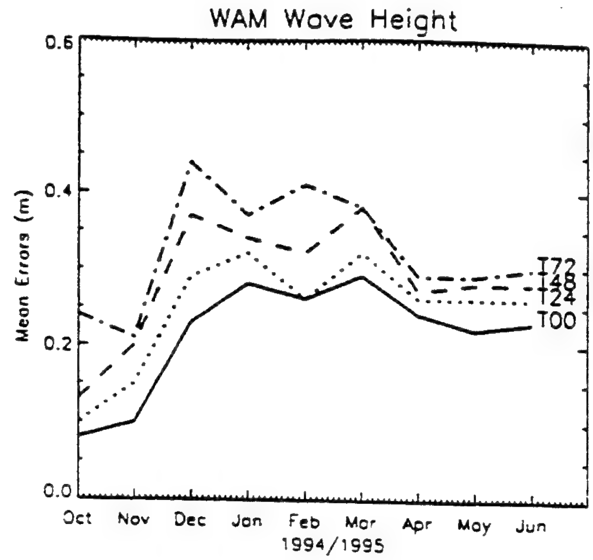

Fig. 6(c). Monthly averaged mean significant wave height errors for GWAM for forecast times of 0 (solid), 24 (dotted), 48 (dashed) and 72 (dash-dot) hours based on comparison with all available moored buoy data in the North Atlantic and North Pacific from October 1994 through June 1995.

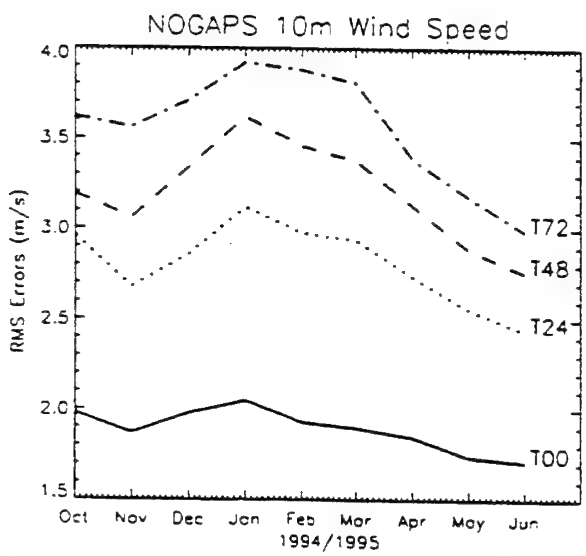

Fig. 6(b). Same as Fig. 6(a) but for wind speed at 10 m height predicted by NOGAPS.

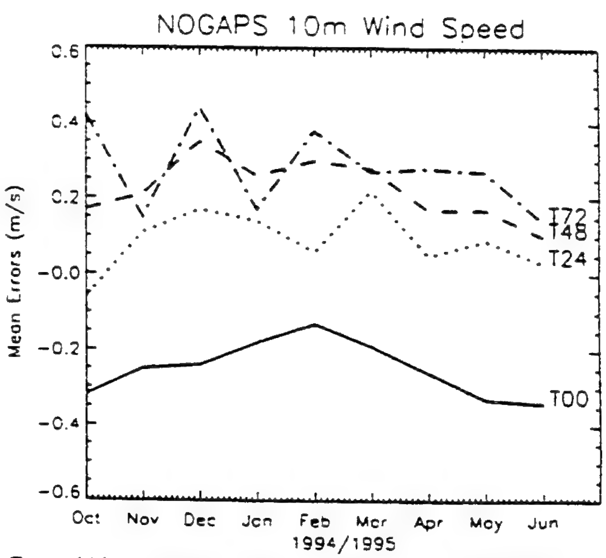

Fig. 6(d). Same as Fig. 6(c) but for wind speed at 10 m height predicted by NOGAPS.

During the spring of 1995, directional wave energy spectra predicted by GWAM were compared with data produced by National Data Buoy Center (NDBC) directional wave buoy 46042, located offshore of Monterey, CA, near 36.75°N, 122.40°W. The water depth at this location is 2103 m and there are no islands to the west which would interfere with swell propagation. The model predicted spectra were simply taken from the GWAM gridpoint closest to the buoy (37.00°N, 123.00°W). Comparisons were made for an

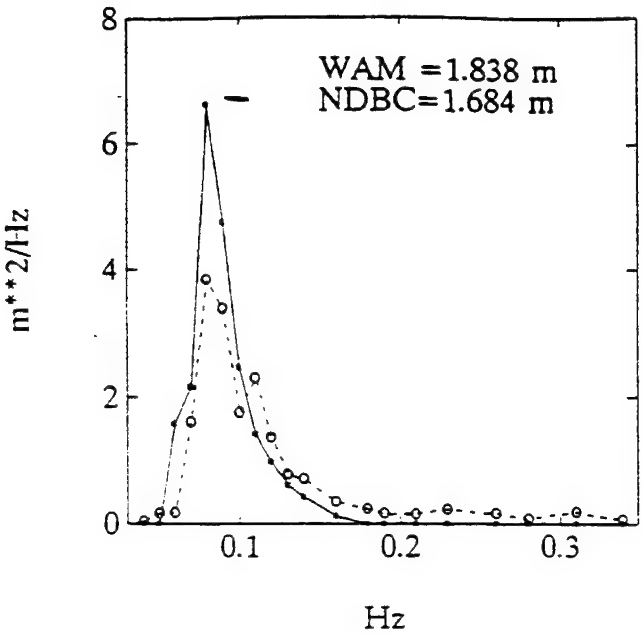

Fig. 7(a). One-dimensional wave energy spectrum observed at buoy 46042 near Monterey, CA, at 0000 GMT 1 June 95 (dashed line and circles) and corresponding 6-hour prediction from GWAM (solid line and asterisks).

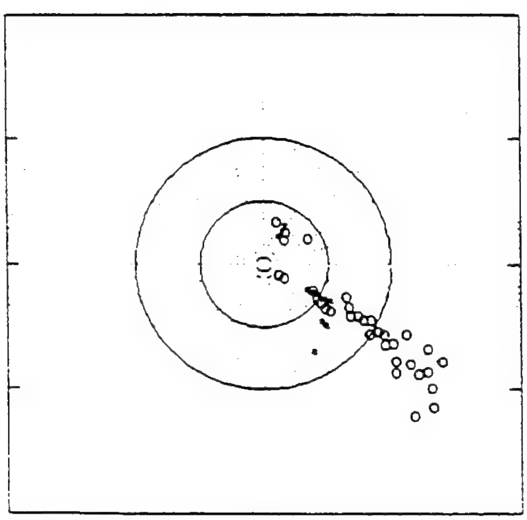

Fig. 7(b). Peak wave energy direction relative to true north for each frequency bin observed by buoy 46042 (circles) and corresponding 6-hour prediction from GWAM (asterisks) for 0000 GMT 1 June 95. Wave frequency increases linearly with radial distance from the center of the polar plot from 0 Hz at the center to 0.4 Hz on the outermost ring. True north is taken as vertically upward on the page, and the convention adopted is to display the directions toward which the wave energy is propagating.

8 day period, from 31 May 95 to 7 June 95, during which time significant wave heights ranged up to about 2 m.

Figure 7(a) shows the comparison of the GWAM and buoy wave energy spectra for 0000 GMT 1 June 95. The agreement, in terms of spectral shape and peak frequency, is very good. However the total wave energy predicted by GWAM tends to be slightly higher than that observed by the buoy. The directional comparisons are shown in Figure 7(b). The buoy does not measure the full directional spectrum, only the peak direction for each frequency bin. Agreement of the peak directions predicted by GWAM with those observed by the buoy is generally good. Note the presence of low frequency swell from the southwest and higher frequency windsea from the northwest, which is typical of spring conditions off the coast of California.

5. SUMMARY AND OUTLOOK

Ocean wave modeling has been an integral part of Fleet Numerical's operation for over 30 years. Through a succession of upgrades to both wave models and the meteorological models that drive them, the accuracy of the wave predictions produced by Fleet Numerical has improved steadily. At present, Fleet Numerical employs the advanced third-generation wave model WAM in both global and regional implementations, with wind-stress forcing provided by the NOGAPS global and NORAPS regional meteorological models.

To address the problem of underprediction of peak wave-height events, the GWAM will soon be "loosely coupled" with NOGAPS in that the surface roughness predicted by the wave model will be provided to the NOGAPS boundary layer for use in its wind stress calculation (see Clancy and Plante, 1993). Also, a higher order propagation scheme, which reduces numerical dissipation (Bender and Leslie, 1994), will be tested in GWAM.

Other future enhancements in wave modeling at Fleet Numerical are expected to include assimilation of wave-height data from satellite altimeters, coupling with surface current models to account for wave/current interactions, and implementation of any improvements to the WAM wave growth, dissipation and propagation algorithms that emerge from R&D. The spatial resolution of GWAM will be increased to 0.75° and, eventually, 0.50° to keep abreast of the increased spatial resolution expected in NOGAPS. Additional fully-automated high-resolution regional applications of WAM may be implemented in response to new

requirements. Finally, WAM, or a similar wave model, will be integrated into the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) model (see Hodur, 1993). In this way, COAMPS will provide the very high-resolution, two-way interactive and internally self-consistent wind/wave products for the coastal regions of the world on which the Navy is now focused (Clancy and Plante, 1993).

6. REFERENCES

Bayler, G. and H. Lewit, 1992: The Navy Operational Global and Regional Atmospheric Prediction Systems at the Fleet Numerical Oceanography Center. *Weather and Forecasting*, 7, 273-279.

Bender, L.C. and L.M. Leslie, 1994: Evaluation of a third generation ocean wave model for the Australian region. Bureau of Meteorology Research Centre, BMRC Research Report No. 43, Melbourne, Australia.

Clancy, R.M., J.E. Kaitala and L.F. Zambresky, 1986: The Fleet Numerical Oceanography Center Global Spectral Ocean Wave Model. *Bulletin of the American Meteorological Society*, 67, 489-512.

Clancy, R.M. and P.A. Wittmann, 1990: FNOC implements advanced wave model. *Naval Oceanography Command News*, **10(11)**, 1-4.

Clancy, R.M. and R.J. Plante, 1993: Evolution of coupled air-sea models at Fleet Numerical Oceanography Center. Proceedings of the MTS'93 Conference, 22-24 September 1993, Long Beach, California, Marine Technology Society, 1828 L Street NW, Suite 906, Washington, DC 20036, pp. 284-290.

Copeland, J.L. and R.J. Plante, 1994: The development of an integrated environmental data base for Navy operational production computers into the 21st century. Proceedings, Tenth International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography and Hydrology, American Meteorological Society, 45 Beacon Street, Boston, MA 02108-3693, pp. 278-282.

Hodur, R.M., 1987: Evaluation of a regional model with an update cycle. *Monthly Weather Review*, **115**, 2707-2718.

Hodur, R.M., 1993: Development and testing of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). Technical Report NRL/MR/7533-93-7213, Naval Research Laboratory, Monterey, CA 93943-5502, 81 pp.

Hogan, T.F. and T.E. Rosmond, 1991: The description of the Navy Operational Global Atmospheric System's spectral forecast model. *Monthly Weather Review*, **119**, 1786-1815.

Janssen, P.A.E.M., 1994: Results with a coupled wind wave model. ECMWF Technical Report No. 71, European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, Berkshire, RG2 9AX, England.

Plante R.J. and R.M. Clancy, 1994: An overview of operational prediction capabilities at Fleet Numerical Meteorology and Oceanography Center. Proceedings of the MTS'94 Conference, 7-9 Sep 94, Washington, DC, Marine Technology Society, 1828 L Street, NW, Suite 906, Washington, DC 20036, pp. 352-358.

Plante, R.J., 1995: Operational predictions for expeditionary warfare. *Sea Technology*, 36, 23-31.

WAMDI Group, 1988: The WAM model - A third-generation ocean wave prediction model. *Journal of Physical Oceanography*, **18**, 1775-1810.

Wittmann, P.A. and R.M. Clancy, 1993: Implementation and validation of a global third-generation wave model at Fleet Numerical Oceanography Center. In *Ocean Wave Measurement and Analysis*, Proceedings of the Second International Symposium, 25-28 July 1993, New Orleans, O.T. Magoon and J.M. Hemsley, Editors, American Society of Civil Engineers, 345 East 47th Street, New York, NY 10017-2398, pp. 406-419.

Zambresky, L.F., 1989: A verification study of the global WAM, December 1987 - November 1988. ECMWF Technical Report No. 63, European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, Berkshire, RG2 9AX, England.

Appendix G

Numerical Modelling of Water Waves–Some Models and Some Problems

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Introduction

In the past 15 years, the modelling of water waves has improved tremendously. Phenomena not fully treated in the past have been included into models, such as diffraction and spectral effects, and the growth of computing power on the desktop and the speed of supercomputers have permitted models to be built that could not have been in the past.

Concurrent with the new modelling technologies, a lot of hard work have provided unprecedented field data and lab data for comparisons of models.

In this presentation, I will review some of the recent progress in wave modelling and types of models that are available and then talk about problem areas that still need to be worked on.

Models and Examples

The problem with wave modelling is that we should be integrating the equations of motion and the conservation of mass over three often very large dimensions. Models often need to cover horizontal areas that are many kilometers in each dimension. This leads to large models in the computational sense, large data requirements, and lots of computer time.

There are many types of wave models: they solve different equations: Laplace, mild-slope or Boussinesq, they are valid in different water depths (shallow water models versus intermediate), they are linear or nonlinear, and they are monochromatic or spectral. They are unidirectional or directional and they can be in the time domain or in the frequency domain. I will review a few of these.

Wave Ray and Parabolic Models

The earliest models of wave propagation were based on the optics analogy and ray tracing. Ray tracing could start in the ocean and trace the rays (or wave fronts) to shore, or back track to see from a given shore point. The problems associated with these models were that only wave refraction was included and that the wave rays had a tendency to cross, leading to problems in interpretation-that is, we predict infinite wave heights. In 1980s, Mei and Tuck (1980) for the Laplace equation and Radder (1989) for the mild-slope equation initiated the use of the parabolic method for wave modelling. Not only did the parabolic equation method provide a faster numerical algorithm to solve the relevant wave equation, but the models included diffraction implicitly.

One successful production model that resulted from the effort is REF/DIF, developed at the University of Delaware. This well-maintained and documented parabolic model has an interesting history. A research version was funded in the 80's by ONR (Kirby and Dalrymple, 1983), then the development of a production model was funded by Exxon Production and Research (with Marty Miller as project monitor) over the course of several years. Since that time, it has been held together largely by Jim Kirby and small grants, most coming from the

Corps of Engineers or consulting contracts. It now is released as version 2.4 and available (Kirby and Dalrymple, 1994).

One of the better known examples of how well it performs is the first test we made of it in 1983. (compare BBR shoal, refraction/diffraction)

This model has been used in the design at Kings Bay and the Port of Toronto, Canada (Baird and Associates)

Parabolic spectral shoaling models, involving the superposition of linear solutions to the mild slope equation of many different frequencies, have been carried out by Panchang, Wei, Pearce and Briggs (1990) for comparison to laboratory wave data. A linear parabolic model was run for many directions and frequencies. The amplitude of a wave within a frequency/direction bin was given by $\sqrt{2E(\sigma)D(\theta)\Delta\sigma\Delta\theta}$. The results of the many model runs were summed at a given location for the significant wave height,

$$H_s^2 = \sum_{i=1}^{n} H_i^2 \tag{1}$$

where n is the number of model runs used (up to 615). They found good agreement with the laboratory data.

REF/DIF S (Kirby and Özkan, 1994) is an extension of the REF/DIF model to conveniently cope with directional sea-states and wave breaking. The model integrates all frequencies at once, therefore it is easy to compute the local wave height. A Thornton-Guza type of breaking model is included. Comparisons to nonbreaking cases of irregular waves propagating over a shoal (Vincent and Briggs, 1989) show a good comparison for the non-breaking wave case; however for wave breaking, the model is not so successful, even with nonlinearity is included.

Boundary element methods provide a convenient method of solving the Laplace equation exactly by integrating over the boundaries of the domain. From the first working models of Longuet-Higgins and Cokelet (1976) and Dold and Peregrine (1986), Grilli, Skourup and Svendsen (1989) are some of the first to develop a numerical wave tank to examine 2-D behavior of waves in ideal fluid–no viscosity. Comparisons with wave data show excellent agreement (*e.g.*, solitary waves in a tank, Grilli *et al.*, 1994), even when there is flow separation, Driscoll, Dalrymple and Grilli (1992).

Boussinesq Models

Boussinesq models were developed for the propagation of shallow water waves (see Peregrine, 1967, for the equations for variable water depth, based on the use of the depth-averaged velocity as a variable). These equations are distinguished by the use of two parameters to describe their validity, the relative water depth $\mu = kh$, where k is $2\pi/L$, L is the wave length, and h is the depth. For Boussinesq theory, μ is small. The other parameter is $\delta = a/h$, where δ is also assumed to be small. Also these parameters are assumed to be related by $\mu^2 = \delta$. These restrictions on μ and δ limit the theory to shallow water.

The Boussinesq models have however been shown to be very robust. Freilich and Guza developed spectral version to examine the shoaling of normally-incident wave spectra. A parabolic form by Liu, Yoon and Kirby allowed obliquely incident waves and compared well with the laboratory data of Whalen. This approach used in the field by Elgar and Guza (1985, 1986), showing good predictions of spectra, bispectra and third-moment statistics.

Attempting to ease the restrictions on depth, Madsen, Murray and Sorensen (1991) and Nwogu (1994) presented two different approaches extending the validity of the Boussinesq equations into deeper water; that is increasing the size of μ. The result was that the extended equations could model the phase speed of waves in intermediate depth as well as linear wave theory could – that is correctly modelling the dispersion of the waves with frequency. The Nwogu methodology, based on developing the equations using the velocity measured at a given depth into the water column, rather than the averaged velocity as was used by Peregrine, was used as a starting point by Wei and Kirby (1995), who developed a fully nonlinear version of the extended Boussinesq equations (FNBM).

This model is presently been tested at the University of Delaware and the University of Rhode Island for coastal use. One of the comparisons is the examination of waves up to the breaker line using the new equations and model and also the fully nonlinear boundary element method (FNPF) to compare.

A comparison to shoaling spectra by Kirby and Wei (1995) required the incorporation of breaking in the model. Following Zelt (1991) and Heitner and Housner (1970), a simple eddy viscosity term is added to the extended Boussinesq equations. The eddy viscosity is turned on by rapid variations of the water surface.

Within the surf zone, wave breaking creates a radically different wave field. The nonlinear shallow water equations, which predict waves which steepen and break in shallow water have been used by Hibberd and Peregrine (1979) to predict bores in the surf zone. The methodology involves numerical integrations with the Lax-Wendrof technique, which preserves 'shock' fronts across the surf zone. Packwood (1983) added friction and permeability to this model, while Ryrie (1983) allowed for oblique incidences.. Engineering models of this method for regular and irregular waves, including time dependent swash oscillations and set-up, have been developed by Kobayashi, Otta, and Roy (1987) and Kobayashi, Cox, and Wurjanto (1990). Their models are IBREAK and RBREAK.

CFD Approaches

In the areas of turbulence and aerodynamics, "computational fluid dynamics" describes the use of numerical codes to predict the fluid behavior. Small beginnings have occurred in the field of wave mechanics. Early in the history of numerical modelling, Hirt xxx at Los Alamos National Laboratory developed the Marker-in-Cell approach to describe free surface flows such as might occur with dam break problems. Later Hirt and Nichols developed the *Volume of Fluid* approach, which has recently been used by Delft Hydraulics to examine waves on steep beaches. van Gent, Tönjes, Petit and van den Bosch (1994) have developed the SKYLLA model, which can predict wave overtopping and allows for the flow field to become disconnected–so that ponding can occur on a berm and air can be entrapped by the breaking process, for example. Applications so far have been limited to 2-D and very near shore problems.

Spectral Models

STWAVE HISWA REFDIF s

Things Left Undone

Numerical Accuracy

All numerical models are based on differencing wave equations or numerical integrations. While these models have often been checked over simplistic bathymetries for idealized cases, how well do they work for large areas. For example, most parabolic models are second order accurate in Δx, the propagation step size. What is the error after many kilometers?

Scintillation

With the wide-spread use of wave models over large areas, one significant problem is the reliability of the model output. One significant input to all of the models is the water depth over a large area. These depths often are from hydrographic charts that have been compiled over long periods of time, or with large sampling intervals. How sensitive are the models to our uncertainty in the bathymetry?

Holthuijsen and Booij (1994) recently examined the influence of bottom perturbation on wave ray and the HISWA model. They refer to this problem as *scintillation*[1] in analog to the scintillation of stars due to fluctuations in the atmosphere. For the ray tracing example, the wave field over a circular shoal on an otherwise flat bottom (20 m) was examined. The case of an unperturbed bottom was compared to 25 different realizations generated by superimposing Gaussian noise (with a 0.5 m std deviation) to the bathymetry. The results show that adding this 2.5 % variation to the bottom results in a large variation in the standard deviation of the wave height–upwards of 36% in the lee of the shoal! For a directional sea-states, the results are much less–20% standard deviation in wave height.

For a realistic example of the North Sea, they compared unperturbed bottom results to those with about a 3% variation in the bottom. Wave heights for long-crested waves varied by the same amount, while for short-crested waves the surface perturbation was about 1%. One surprising result is that the amount of wave height variation increases with the increasing resolution of the model, since both the water depth and the bottom slope affect the model.

At Delaware, we have been examining REF/DIF and WANGLE (a Fourier-Galerkin model) for the same case of the circular island to see the model dependencies in the scintillation effects. We find that the REF/DIF model has far less susceptibility to scintillation effects than a ray tracing model. Note that directionality, nonlinearity and diffraction all serve to reduce the effects of scintillation.

[1] They attribute the first use of this term for wave models to K. Hasselmann.

Chaotic Behavior

The tangled web of wave rays that results from ray tracing has always been a problem for interpretation. Crossing rays lead to the dilemma of infinite wave heights. To surmount this problem–Battjes and Bouw suggest averaging over a finite region. However, recently, work has shown that in fact the ray tracing problem does lead to chaos. Brown, Tappert, and Sundaram (1991) examine waves propagating over a doubly periodic bottom,

$$h = h_o(1 + \epsilon \cos \frac{2\pi x}{W} \cos \frac{2\pi y}{W})$$

They find, for their test case, that, after the waves propagate for seven minutes (corresponding to a distance of less than 100 wave lengths), the wave directions become independent of the initial conditions, for reasonably large values of the bottom perturbation: $\epsilon/h_o > 0.13$. How this applies to the other models that exist or in fact to nature is not known and needs to be examined.

Irregular, Reflective or Absorbing Shorelines

The shorelines of interest are often convoluted or interrupted by the presence of an inlet. These shorelines do not lend themselves to easy analysis by numerical models based on rectangular grids. Conformal mapping in one means to 'straighten' out the shoreline, and has been used for tidal modelling. Kirby, Dalrymple and Kaku (1994) provide the mild-slope equation after a generic coordinate transformation and specifically develop parabolic models for conformal domains. This still needs to be implemented for design models.

For specified geometries, special models can be built. Dalrymple and Martin (1995a) show the propagation of waves into the mouth of the inlet; while Dalrymple and Martin (1995b) show the wave field behind an inlet. This model is restricted to vertical fully reflecting boundaries.

Melo and Guza (1991 a,b) show that the dissipation of wave energy within the rubble-mound lining of an inlet is very intense. Attempts to model this behavior (Melo and Guza, 1991b;Dalrymple, 1992; Martin and Dalrymple, 1994) have shown significant promise, but are strictly developed for specialized cases.

Models that require shoreline and or lateral boundary conditions must take into account partial reflecting or absorbing boundary conditions. Specifying these conditions is not easy.

Wave Breaking

Waves break due to limiting depths, opposing currents and a surfeit of energy (white-capping). These effects are not adequately addressed in most models, particularly the last two.

Depth limited breaking is included in wave models in a variety of waves. The simplest is to reduce to wave height to some percentage of the water depth (the so-called spilling breaker assumption). A slightly more sophisticated treatment for a monochromatic sea state is the model of Dally, Dean and Dalrymple (1984), which dissipates wave energy in a more realistic fashion than the spilling breaker assumption. For spectral seas, the Battjes and Janssen model or the Thornton-Guza model provide similar wave height decay for normally incident wave spectra.

For Boussinesq models, where the models are stepping in time, the breaking of an individual wave can be calculated by the Schäffer model or the Zelt model used by Wei and Kirby. The first of these works by examining the local slope of the water surface and when it exceeds a

certain value, the wave height is reduced based on a roller concept (Svendsen, 1984). The Zelt model adds a viscosity to the wave field when a critical value is exceeded.

How well do these models handle oblique breaking. Or the breaking of a three-dimensional sea state as in the Vincent and Briggs experiment. Plunging breakers. All of this work needs to be done. Further, within the surf zone there is a considerable amount of turbulence and 3-D currents engendered in the breaking process.

In the vicinity of tidal inlets, tidal currents are rapidly varying in space and time. At numerous locations the ebb currents are fast enough to arrest incoming waves causing blocking and breaking. This effect is not in most models, but clearly needs to be. At the present time, work is on-going at CERC (Briggs) and at UD (Kirby).

0.1 Swash

3-D swash

Wave-current interaction

Waves that encounter a current change length and size. For idealized cases of vertical variation in current over the depth, this effect is reasonably well-understood (Miles, Longuet-Higgins, Dalrymple, Kirby); however, for the case of horizontally spatially-varying current fields, there is very little theory. Booij, Kirby and REF/DIF. Near tidal inlets or in straits, this is a big problem.

There are also effects due to stratified flows. Deep inlets are often stratified. How does that effect the wave field? I am aware of no on-going work in this area.

Nonlinearities

The sea surface is nonlinear. Almost all spectral models are linear, due to the need to superimpose solutions. How serious an error? If you have the choice between nonlinear and unidirectional waves versus directional sea-states and linear waves, the best choice is the latter, as directionality tends to smooth out the wave field.[2] However, nature is nonlinear and directional. Both need to be included.

Boussinesq models can include both, to a certain extent.

Need higher order in μ Boussinesq equations.

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[2]This same answer applies to diffraction and monochromatic wave versus directional sea-states.

Offshore Boundary Conditions

Wave models have to be specified with boundary conditions. Alongshore boundary conditions, shoreline boundary conditions and offshore boundary conditions all create problems.

Parabolic models (Stokes or Boussinesq) have a significant advantage that the shoreline boundary condition is not necessary and offshore only an incident wave field must be specified, as there are no seaward propagating waves.

Elliptic (Laplace) and hyperbolic (Boussinesq) models require that the incident wave field be specified and that conditions be placed on the offshore boundary to ensure outgoing waves. This is often accomplished with the Sommerfeld radiation conditions.

The Boussinesq equations require knowledge of the offshore water surface elevation and velocity. However, specifying both leads to numerical noise. The equations appear to be 'incompletely parabolic,' (McCalpin, 1995), and existence and completeness proofs do not exist. There is room for improvement here.

Field Testing

The most important activity in model building is testing the model. Simple cases have to be done early in the testing phase; the last step is usually testing against field data. The problem is how to do the testing. Wave modellers typically have grided the study domain into thousands of offshore grid points with hundreds along the offshore boundary. How are these to be input into the model. How are the data to be compared? If it is a time dependent model, then we need to compare measured wave heights with respect to time versus predicted. The problem is that in the field the offshore wave field is directional, and it is impossible to know all the components of the spectrum. Measurements at an offshore linear array would be useful, but unless there are as many array elements as offshore grid points in the model, then there will always be uncertainties.

Acknowledgments

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Appendix H

An Overview of Processes That Modulate Short Surface Wave Energy

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(1) The analytical and numerical models, 3GWAM, REFDEF/REFDIFS, COAMPS, NOGAPS, etc. are only as good as the current understanding of the physics that are being modeled. As more extensive laboratory and field experiments are performed and computational methods become more powerful, the modeling of these terms will improve dramatically. One of the first goals of the AN-WPG should be to define where they can have the greatest impact on improving the modeling by increasing the physical understanding of the terms in the models within the monetary limitations of the program. The time scale for this process is fairly short which implies that currently archived, high quality data sets should play an important role in the process as well as currently ongoing projects that are directly related to the effort. Placing the AN-WPG program in a position to take advantage of, or share results with these programs should be a high priority. Related efforts at NRL include:

-High resolution remote sensing ARI (FY 91-95)
-Physics of coastal remote sensing RO (FY 96-00)
-Ocean turbulence and fine structure ARI (FY 93-97)
-Forced upper ocean dynamics of the Arabian SEA ARI (FY 94-98)
-Hyperspectral remote sensing of the coastal environment (FY 96-00)
-Coupled coastal-deep water regimes ARI (FY 96-00)
-Cooperative SAR program in support of coastal warfare and ship detection (FY 95-99)
  (a) Joint program between US, Norway NDRE, and UK DRA with four objectives;
    (i) littoral oceanography
    (ii) ship wake detection and characterization
    (iii) sea bed topography
    (iv) acoustics

-SIR-C, X-SAR program to study physics of ocean surface features (FY 95-96)
-NAOS (non-acoustic ocean signatures) program to study ocean/littoral signatures
-NASE (non-acoustic surface effects) modeling lab numerical capabilities;
  (i) shallow water wave modeling
  (ii) 3-D + time flow, currents, and sediment transport modeling
  (iii) radar signature modeling of water surface features

-SEALAB (special environmental applications lab). The group performs research in the application of satellite remote sensing techniques to environmental and coastal/littoral

problems. Current projects include feature extraction and topography from SAR images, including polarimetric, interferometric spot and strip map SAR's.

(2) Coastal and open ocean processes take place on dynamically important scales ranging from tens of meters to tens/hundreds of kilometers. These processes evolve simultaneously over broad time scales and the resulting remote sensing imagery can be a very complicated superposition of the dynamics across many scales. Since the smaller scale processes/features are dynamically coupled to the larger scale phenomena, it is important that proper modeling and description of these processes be performed within a merged environment rather than in isolated pieces. Both direct, in-situ and remote sensing platform data need to be simultaneously gathered to help understand the physics and dynamics across these scales and then these results need to be incorporated into the merged models. The merging of data from satellite, air-borne and ship-borne remote sensing platforms and in-situ sensors in combination with the merging of analytical/numerical models of vastly different scales will be necessary to accurately predict the dynamics of the open and coastal oceans. NRL has a significant remote sensing and in-situ measurement capability that can be used to support the data fusion and modeling effort. A summary of NRL's measurement capabilities follows:

-PHILLS (portable hyperspectral imaging low light spectrometer); can be used to detect breaking, broken, non-breaking surface waves and foam. The near IR signature provides very strong wave signatures.

-Oceanographic instrumentation carried aboard the NRL P-3;
- (i) X-Band RAR; calibrated/navigative dual-pol imaging RAR that measures surface roughness and directional wave spectra.
- (ii) Ku-Band scatterometer.
- (iii) PRT-5 radiometer.
- (iv) Laser altimeter.
- (v) NOAA-SeaWiFS multispectral imager.

-AMPS (airborne multispectral pod system) and Ku-Band SAR; calibrated/navigative 1m or 3m resolution SAR.

-AMPS LIDAR; aircraft mountable LIDAR system to measure surface roughness.

-LIDAR; shipboard/field LIDAR system for measuring aerosols and particles.

-Passive millimeter wave radiometers; high resolution, multi frequency radiometers for measuring surface foam coverage and the location of wave breaking.

-TOAD (towed acoustic Doppler); measures water velocities.

-STAR (surface towed array); measures water temperature and salinity.

-STEMS (surface tension measuring system); measures water surface tension and also carries a downward-looking, acoustic bubble profiler.

-Buoy deployed, laser-slope scanning gauge; measures slope spectra in the 1 - 100 cm wavelength range.

-Ship-mounted, optical wave imager; measures wave slope spectra in the 1 - 100 cm wavelength range.

Additional capabilities that NRL has direct access to through existing programs include:

-NADC SAR: multi frequency, multipolarization X, L, C, band SAR that can be operated in strip, spot and interferometric modes.

-JPL interferometric SAR.

-OSCR high frequency, moderate resolution ground based radar system that measures surface wave speed and wave spectra.

(3) Accurate prediction of the nearshore/surf zone characteristics, wave height, wave direction and currents are critical for supporting amphibious landing and mine countermeasure operations. These predictions can lead to a better understanding of the surface signatures of bottom topography and submerged obstacles, drifting mine trajectories, rip and longshore currents, breaking wave bubble fields, water clarity and sediment transport. Accurate prediction of the flow (currents and tidal) and surface wave state modifications around/over large-scale obstacles/features (islands, banks and canyons especially) are equally important for Navy operations.

(4) The following are a condensed list of some of the important 6.1 type, scientific issues relating to short waves at the ocean surface. The list is by no means complete.

(i) Wave growth; mechanisms of energy transfer from wind to waves, especially in the capillary region remain to be explored, especially we need to know the growth rates with pre-existing swell conditions and under low wind conditions. Current expressions for growth rates are inadequate.

(ii) Surface tension effects; short waves are damped significantly when natural and/or petroleum oil films are present at the surface. What are the mechanisms responsible for this damping and how should they be included in the models.

(iii) Wave-current interactions; how far apart in wave number space do short waves need to be from swell before they cease to interact with each other, and how do currents effect the growth and dissipation of short waves and the energy transfer to different wave number scales.

(iv) Wave-turbulence interactions; how does turbulence influence the growth and decay of short waves and the energy transfer to different wave number scales.

(v) Wave directionality; the directionality of the wind-wave spectrum needs to be studied under the following conditions. If a swell wave, or spectrum of swell waves, is introduced into a preexisting wind-wave field, how is the pre-existing field modified. Conversely, if wind is blown over an existing swell field, how do the wind wave develop.

(vi) Water temperature effects; theoretical models have postulated a dependence of short wave energy on water temperature due to changes in water viscosity with temperature. Is there such a dependence and if so how does it influence short wave energy.

(vii) Stability of the air-sea interface; the air sea temperature difference has significant influence on the wind energy input to the short waves.

The following is some background information that I put together on short surface wave modulations. Feel free to use any of it in your report. It is by no means an exhaustive review.

Interest in the modulation of short waves on the ocean surface has increased recently because of the importance of short-wave dynamics for active microwave remote sensing of the sea surface. Features such as long-wavelength swell, ocean current fronts, ship wakes, internal waves, bottom topography, coastal processes, thermal fronts, ocean wave spectra and surface slicks are all sensed indirectly by their influence on the short waves responsible for detectable backscatter at steeper grazing angles.

1. Wind energy (wave growth/relaxation)

I. wind speed, fetch and duration

Wind waves are generated by wind blowing at some speed across the sea surface over some linear distance (fetch) for some period of time (duration). Depending on the conditions, the sea can either be fully developed or non-fully developed if there are fetch or duration limits at a given wind speed. For an in-depth discussion on fetch and duration limited wave forecasting, the reader is referred to Chapter II in the book by Pierson et al. (1984). For this paper we will limit ourselves to an abbreviated discussion on the formation of short gravity and capillary waves by wind.

The initial generation of wavelets appears to be through the mechanism of instability of the interfacial, laminar shear layers at the coupled air-water interface or by a resonance with the downward flux of momentum through fluctuations of the pressure field (normal stresses) in the atmosphere. The work of Kahma and Donelan (1987) indicates that the inception wind speed (light winds) for microscopic capillary-gravity waves is only about 0.7 m/s. The first waves to grow have wavelengths of 5 - 10 cm. Given enough fetch, these waves can grow to a point where their amplitudes exceed the depth of the viscous sub layer (~3 mm). At this point their growth is balanced by viscous damping, they are hardly noticeable by eye or radar, and the efficacy of the laminar shear flow instability may be drastically reduced. It is therefore unlikely that these growth mechanisms will be effective in amplifying the waves further to a point where they are observable by eye or microwave backscatter radar. Higher winds and exponential growth by direct wind input will then be required to overcome the viscous damping and amplify the initial wavelets to a point where the surface becomes roughened enough such that the short waves are visible to the eye or radar sensors. At wind speeds above a few meters per second, the high wave-number part of the spectrum (wavelengths < 30 cm) aligned with the wind receives energy from the wind and loses energy through dissipative processes, mainly viscosity and micro breaking. At higher wind speeds, the wave growth rate due to wind is a strongly increasing function of wind speed and wave frequency. This is the reason why C and X band waves grow more quickly than L band waves in a freshening wind on a clean water surface. The shortest waves may also be significantly affected by the turbulence generated by larger-scale breaking waves if these breaking waves are present. In addition to the high wave-number part of the spectrum being highly wind speed dependent, it is also dependent on surface temperature, surface contamination, and wind stability and gustiness that may be related to the recent history of the passage of air over the terrain surrounding the water body. These additional mechanisms will be discussed shortly.

Winds over the ocean surface are generally unsteady (gusty) especially at low wind speeds (as illustrated by the appearance of transitory cats paws) where the standard deviation of the wind speed may be as large as 50 percent of the wind speed itself. Short wave and ripple growth are coupled with the unsteadiness of the wind. Under the same average wind stress conditions, ripples will be amplified quicker under fluctuating wind conditions. Researchers often define a critical wind speed as that wind speed required to generate visibly perceptible wave-like surface patterns that are progressive in the wind direction. It is around this wind speed that there is a transition from wave generation in the laminar boundary layer by laminar shear flow to wave generation by fully turbulent flow. Wave tank measurements have shown this value to be around 3 m/s. These measurements are generally fetch limited and field observations that are not fetch limited have shown values for the critical wind speed that are somewhat less. Donelan and Pierson (1987) similarly define a threshold wind speed in their paper as the minimum wind speed where there will be measurable Bragg radar backscatter.

ii. water temperature and salinity

The kinematic viscosity (n) of water changes considerably with temperature, from 0.8×10^{-6} m^2/sec at 30 degrees C to 1.8×10^{-6} m^2/sec at 0 degrees C. The viscous decay rate of surface waves per unit wavelength, 8pnk^{2}w where w is the wave frequency and k is the wave number, is very important in the gravity-capillary wave regime. Because the short wave viscous dissipation rate increases rapidly with wave number, k, the wavelength of the initial waves should also be longer at lower temperatures. This temperature dependence will also result in increases in the inception, critical and threshold wind speeds as the temperature decreases. As an example, Khama and Donelans' (1988) measurements show that the critical wind speed increases from 2.9 m/s at 35 degrees C to 3.5 m/s at 4 degrees C at a fetch of 4.7 m in their wave tank as a result of the increased viscous dissipation. Donelan and Pierson (1987) present two graphs that summarize their model calculations to examine the influence of water temperature, incidence angle, and salinity on the threshold wind speeds for significant Bragg backscatter at L, C, X, K_u, and K_a bands. At 20 degrees incidence, the effect of decreasing the water temperature from 30 degrees C to 0 degrees C is to increase the threshold wind speed at L band from 1.7 to 2.0 m/s, at C band from 1.7 to 2.2 m/s, at X band from 2.0 to 2.8 m/s, at K_u band from 2.2 to 3.1 m/s, and at K_a band from 3.7 to 5.4 m/s. Donelan and Piersons' (1987) model calculations also show that for wind speeds of 6 to 12 m/sec, the backscatter will be several decibels higher over warm water than over cold water for the same wind speed and incidence angle. Their model predicts that water salinity has a negligible effect compared to temperature on the threshold wind speed for significant backscatter.

Huhnerfuss et al. (1994) have recently performed experiments to study the influence of water temperature on the wave damping characteristics of the different fractions of biogenic sea slicks. In general it has been assumed that increasing water temperatures give rise to a more homogeneous distribution of surface active compounds on the surface, and that these films become more elastic and the kinks become more important. Their results show secondary temperature effects on the wave damping in the range of temperatures (9.0 to 17.4 degrees C) encountered during their experiments. They attribute these effects to the temperature influence on the film's

morphology, the arrangement of the film forming compound at the air/water interface. They stress that more experiments are needed to further investigate these temperature effects.

iii. atmospheric stability (air/sea temperature difference)

The difference between the air and water surface temperature (atmospheric stability) can have a measurable effect on the radar return over a wide range of wind speeds. For moderate wind conditions, the radar return will be amplified under unstable conditions, where the air temperature is less than the water surface temperature, and suppressed under stable conditions when the water is cooler than the air. At low wind velocities the effects are systematically greater. In addition, with the probable coupling of short waves with wind fluctuations, short waves will be amplified under unstable atmospheric conditions and suppressed under stable conditions under the same average wind stress conditions.

iv. humidity

Geernaert and Larsen have examined the effect of humidity on the momentum flux (wind stress) at the air-sea interface. They show that momentum flux estimates are very sensitive to the relative humidity, the sea air temperature difference and the surface water temperature. They found that the ERS-1 radar cross section, when treated as a function of wind stress (momentum flux), varied significantly with relative humidity, particularly when the surface temperature was warm. For example, for a stable sea-air temperature difference of -3.0 degrees C and a wind speed of 7 m/sec, the difference in radar cross section obtained by using two different definitions of atmospheric stability, the first including humidity and temperature and the second using only temperature, was 1.2 dB for a water temperature of 30 degrees C and only 0.5 dB for a water temperature of 8 degrees C. For an unstable sea-air temperature of +3.0 degrees C the differences were 0.2 and 0.1 dB for water surface temperatures of 30 and 8 degrees C respectively. At lower to moderate wind speeds they speculate that the differences will be more pronounced and they show that at higher wind speeds the effects are significantly reduced.

2. Short gravity/capillary wave damping; sources and modeling

There are two boundary layer related mechanisms responsible for short gravity/capillary wave energy damping within the sea surface microlayer region. These are internal viscous dissipation in the surface boundary layer and surface tension changes created by the presence of monomolecular films of naturally-occurring surface-active materials and/or petroleum oil films from natural seeps or spills on the surface. The following are discussions of each of these mechanisms.

I. damping source: internal viscous dissipation

The first and weakest type of short wave energy dissipation occurs within the surface boundary layer. Lighthill (1979) provides a detailed derivation of the equations describing water-

wave attenuation by viscous dissipation within the boundary layer. The result is that, over one wave period waves loose energy by internal viscous dissipation at a rate proportional to the wave frequency (w) multiplied by the wave number (k) squared, $8pnk^2w$, where n is the kinematic viscosity of water. As an example, deep-water sinusoidal waves with a wavelength of 10 cm will decay by a factor (e = 2.72) in energy after 16 periods if there is no energy input from a source such as wind. From the above relationship, it is obvious that ripples are the most susceptible to viscous damping.

There are circumstances when greatly enhanced dissipation can occur within the surface boundary layer. If there are departures of the surface tension from its equilibrium value in the surface boundary layer, the tangential stress changes from not to zero but to the value $p_{xz} = -dT/dx$ needed to balance the x-component (dT/dx) of surface force per unit area. There are conditions in the surface boundary layer when the resulting surface dissipation, extra viscous dissipation due to enhanced shearing stresses within the surface boundary layer, greatly exceeds the rate of dissipation. These conditions are met when the surface is covered by a thin film of a contaminant such as a monomolecular surface-active film of biological origin or a thicker film of anthropogenic origin (oil spill or seep). Discussions on each of these types of films follow below.

ii. damping source: surface-active films

The thin surface region of the ocean, around 1 mm thick, is referred to as the sea-surface microlayer. The microlayer surface region is a habitat for surface-dwelling marine organisms. It has a greatly increased concentration of chemical substances resulting mainly from biological processes and in some instances, anthropogenic contamination in the form of petroleum oils from natural seeps or spills. These biogenic sea slicks consist of a variety of substances which modify the air/water interface processes more or less intensely. Since the composition of these slicks is related to bioactivity, they show a strong seasonal variation. The analysis of biogenic slicks has identified many substances with varying relative concentrations including amines, amino acids, proteins, carbohydrates (sugars, etc.), triglycerides (fats, fish oils, etc.), phenols, sterols, vitamines, ketones, aldehydes, hydrocarbons, fatty acids (methyl or ethyl esters), and fatty acid derivatives.

In general, a surface-active, polar organic compound contains oxygen with unpaired electrons or some similar hydrophilic group at one end of the molecule and a relatively insoluble hydrophobic segment (tail) such as a straight hydrocarbon chain at the other end. The water-loving end of the molecule could dissolve, but the hydrophobic part prevents complete solubility, hence the molecules form a single layer at the air/water interface. Most surface-active compounds are more attracted to water than to each other and therefore will not spread over their own monolayer. Surface-active compounds can be soluble, however at equilibrium in still systems they concentrate at interfaces. Generally, once a surface-active compound has reached the air/water interface, a considerable amount of energy is required to force it back into solution. The wide variety of compounds in the marine microlayer makes a chemical description of the monolayer very difficult.

The same film-forming compound may be arranged and distributed at the air/water

interface in the following manners:

1. The molecules may be spread homogeneously, forming a film of chemical compounds that is only one molecule thick (monolayer).
2. The molecules may form islands, so-called domains, of different sizes between several microns and several hundred microns; furthermore, the domains may exhibit subcell structures, the two dimensional analogue to crystallographic structures.
3. The hydrophobic chains may be arranged vertically to the water surface or at a defined angle of less than 90 degrees. The respective angle depends on the chemical structure of the film material, the temperature, and the compression status of the slick.
4. The hydrophobic chain may exhibit kinks where the linear arrangement of the chain is disturbed by irregularities which give rise to considerable sterical hinderences and thus to a reduction of the hydrophobic interactions.
5. The head group structure may vary in dependence on the compression status which may include hydration/dehydration effects.

The chemical character of this monolayer controls many of the physical properties of the air/sea interface and plays an important role in wind-wave coupling and the microwave radar ocean backscatter cross section. The physical properties that govern the behavior of short gravity/capillary waves at the water surface are surface tension (surface film pressure), surface elasticity, and surface viscosity. These properties are most affected by the chemical composition and concentration of the materials in the surface monolayer. Molecules within the bulk water column are surrounded on all sides by other molecules that are attracted to them by cohesive forces. Because no molecule is present on the air side of an air/water interface, the surface molecules are attracted inward. Because the result is a minimization of surface area, surface tension forces are treated as forces that act parallel to the plane of the surface along a line. The presence of a single, molecule-thick layer of different molecules on the surface of water alters the balance of forces and reduces the surface tension. Film pressure is defined as the difference between the surface tension of clean water and the surface tension of water covered by a film.

iii. damping source: petroleum oil

As was mentioned in the discussion about surface-active films, the marine microlayer will also contain anthropogenic contamination in the form of petroleum oils from natural seeps or spills. The chemical composition of petroleum oil slicks is radically different from natural slicks and they are generally much thicker. Because of cohesive forces in oil, heavy fuel oil (black oil) spilled on the sea surface can cover large areas with thicknesses measured in centimeters. Relatively thin oil slicks are often detected by observing a silvery sheen or interference colors. These colored oil films are generally hundreds of nanometers thick. Oil films can damp capillary/gravity waves and if they have become partly oxidized and spread thinly enough, the slicked area of water covered by them can be mistaken for a natural film. However, petroleum films with high hydrocarbon content are easily detected by chemical analysis. Another significant difference between an oil slick and a biological surface-active slick is that the oil slick forms an insoluble surface which does not permit diffusion of molecules between the surface and the bulk liquid below. Insoluble surfaces are purely elastic surfaces.

iv. numerical/analytical modeling

To understand the impact of surface films on ocean remote sensing, it is necessary to have an accurate analytical or numerical model relating film properties with the propagation and damping of short surface gravity/capillary waves. Fernandez et al. (1992) and Alpers and Huhnerfuss (1989) compare several analytical and numerical methods for computing the damping effects of a surface film on the short waves. The reader is referred to their papers for a complete description of the methods compared. The physical properties of the surface film that are important for these analyses are the surface tension (T), the surface dilitational modulus (e) which consists of the surface dilitational elasticity (e_d) and surface dilitational viscosity (e_i) and the bulk viscosity of the underlying fluid (n). Physically, the dilitational components relate the ability of the monolayer to contract and expand in response to changes in its surface area (A_e). These properties are related by the following equation,

$$e = dT/(d\ln A_e) = e_d + ie_i.$$

Generally, both e_d and e_i are assumed frequency dependent for wave propagation even though e_d is generally defined by the quasi-static film pressure-area curve. In addition, both these moduli are affected by diffusion which varies from one surface-active film to another. For the simple case where $e_i = 0$, the surface tension responds instantaneously to any compression or expansion. An increase in the surface dilitational viscosity causes the film's response, characterized by a change in surface tension, to lag in time with the change in area. These are soluble monolayers and are representative of most complex, surface-active films of biological origin that are found on the ocean surface. The reasons for this time lag involve the diffusional interchange between the surface and the bulk liquid. Insoluble monolayers such as those produced by an oil slick do not permit diffusion of molecules between the surface and the underlying bulk liquid and therefor do not exhibit surface dilitational viscosity. This is the major difference between biological and petroleum films. There are several experimental methods that can be used to determine numerical values or define empirical relationships for these dilitational quantities. They are outlined in papers by Bock and Frew (1993), Frew and Nelson (1992), and Barger (1991) and will not be discussed here in this paper. In addition, there is a special section of the Journal of Geophysical Research, Volume 97(C4), published in 1992 by the American Geophysical Union that contains thirteen papers dealing with the sea surface microlayer. They are all interesting reading.

In a recent series of laboratory and open ocean experiments to study the properties of artificial slicks on the sea surface, Huhnerfuss et at. (1994) have established a link, for the first time, between elements of the morphological structure of the monolayers and geophysical parameters which are closely related to the wave damping ability of surface active compounds and their influence on ocean radar backscatter. Their results strongly suggest that the molecular structure of the coupled system, organic surface film/water, is important for the viscoelastic properties and thus the wave damping and that the dilitational modulus must be dependent on the morphology of the surface. The molecular structure of the coupled system is dependent on the

subcell structure, morphology and water structure which are determined by the molecular arrangement of the film forming substance (conformation, tilt, headgroup structure), by dynamic processes (compression/dilation, spreading), and by various physical and chemical properties (temperature, pH, salts, dissolved organic matter).

v. affect of surface films on short wind wave growth

When the water surface is calmed by the presence of a surface film, the friction velocity is reduced to a smaller fraction, approximately 80 percent, of the mean wind speed than exists in the absence of a film. For a typical surfactant, this reduction in the growth rate parameter is around 30 percent compared to that of a naturally-roughened, clean surface. In addition to the decreased friction velocity, there is also the increased dissipation rate due to the presence of the surface-active film that inhibits the wave growth. This dissipation is a strongly increasing function of wave frequency. As was the case with wave growth due to wind, the C and X band waves damp much more quickly than L band waves. Therefore, the influence of surface-active films on the growth of short wind waves is a combination of smooth surface effects and wave damping effects. Tang and Wu (1992) have shown that for a natural film in a wave tank, this effect is most pronounced for wind speeds less than 6 m/s and disappear above wind speed greater than 6.85 m/s where the film is most likely to be disrupted and washed down by wave breaking. For artificial films in a wave tank, the data of Alpers and Huhnerfuss (1989) show that a minimum wind speed of 5.5 to 7.0 m/s is required to produce measurable radar backscatter (RCS) and that not until approximately 12 m/s does the backscatter power become equivalent to clean surface backscatter. These differences further demonstrate that wave damping effects are very dependent on film properties.

3. Surface currents

When short, surface waves encounter a region of variable currents, a strong interchange of energy and momentum occurs that results in significant changes to the wave amplitudes, lengths, periods, geometry's and directions. This strong interchange of energy between the short waves and a variable current is mainly the result of continuous refraction and nonlinear interactions. These nonlinear interactions include energy losses as the waves steepen and break at and near the current boundary during the refraction process. In addition, the transfer of short wave energy to different wave numbers and directions during the refraction process results in a significant reduction in the short wavelength components of the incident wave field. For waves in the direction of the current, the reduction is particularly strong. For those waves directed opposite to the current, their wavelengths are reduced as they are refracted (turned away) from the current direction. The relative absence of short wave components with angles close to the current direction will add a directional distribution to the short wavelength region of the spectrum.

4. Attenuation by turbulence

Short water waves are affected by turbulence through both scattering and dissipation of their wave energy. As waves interact with turbulent eddies of similar length scales, their energy can be scattered into different wavelengths and different propagation directions. This can have a

direct influence on the backscattered energy over that region. Turbulent dissipation diminishes short wave energy and will be important for remote sensing of phenomena that change short-wave energy over considerable length scales such as ship wakes, rip currents, channel and river outflows, breaking waves, and wakes created by flows around large obstacles. Turbulence will also affect the growth rate of wind-generated waves. For short gravity/capillary waves, the damping rates due to turbulence can be one or two orders of magnitude greater than viscous damping.

Olmez and Milgram (1992) have recently published a summary of their measurements of the dissipation of short, 6 to 10 cm (4 to 5.3 Hz), non-breaking, monochromatic water waves, by turbulence in a wave tank. Their data support the theory that the dominant mechanism for the dissipation of short wave energy by turbulence is vertical mixing. Most of the energy transfer to turbulence may not occur in the usual energy-containing depth of the short waves, instead it may first be convected downward out of the wave zone by the vertical turbulent velocities. Empirical estimates of the turbulence dissipation rate are also published in the paper.

5. Nonlinear wave-wave interactions

Nonlinear transfer of wave energy through wave-wave interactions and wave breaking are an important term in the equations governing the evolution of the short, surface-gravity, wind wave field and their influence on surface radar backscatter. Nonlinear theories for wave-wave interactions explain how a wave spectrum grows toward low frequencies with increasing fetch and duration as the energy moves from the peak region to both higher and lower frequencies. For ocean waves, the random occurrence of many wave components coming together to produce a highly nonlinear group may then be expected to lead to rapid broadening of the spectral content around the dominant frequency of the group. The transfer of energy from steep, breaking waves to turbulence and higher wave numbers is also a highly nonlinear process. Wave breaking can lead to enhanced backscatter in the breaking region and dissipation of wave energy, hence reduced short wave energy, in the turbulent near-surface region left after the breaking wave passes.

Ocean surface gravity waves evolve significantly as they propagate shoreward into shoaling water. In deep water the wave field is characterized by strong frequency dispersion and broad directional distributions. At second order in weakly nonlinear theory, forced motions arise which can be interpreted as small corrections to the underlying linear wave field. Resonance's between quartets of waves occur at the next higher order, resulting in slow cross-spectral energy transfers. Although energy exchanges are very small on wavelength scales, the frequency directional spectrum is substantially modified over hundreds of wave lengths. In the surf zone, waves are essentially nondispersive, directional distributions are narrow and strong nonlinearities drive relatively rapid spectral evolution. Here models based on nondispersive, nonlinear shallow-water equations for unidirectional waves predict many important features of bore propagation and runup (Kobayashi et al., 1989). Between the strongly dispersive deep water and nondispersive surf zone regimes is the shoaling region, characterized by moderate dispersion, narrow directional spread and substantial nonlinearities. Waves propagating through the shoaling region evolve significantly in several wavelengths, with nonlinearly driven cross-spectral transfers of energy and phase modifications leading to the asymmetric and skewed profiles characteristic of nearly breaking and

broken waves. The short evolution distances and moderate dispersion characteristics of the shoaling region suggest that second order (quadratic) nonlinearities involving triads are important. Elgar et al. (1993) laboratory experiments clearly demonstrate the importance of these triad interactions.

REFERENCES

Abbott, M. B., H. M. Petersen and O. Skovgaard, 1978. On the Numerical Modelling of Short Waves in Shallow Water, J. Hydraulic Res., 16, 173-204.

Alpers, W. and H. Huhnerfuss, 1988. Radar signatures of oil films floating on the sea surface and the Marangoni effect, J. Geophys. Res. 93:C4, 3642-3648.

Alpers, W. and H. Huhnerfuss, 1989. The damping of ocean waves by surface films: A new look at an old Problem, J. Geophys. Res. 94:C5, 6251-6265.

Battjes, J. A., 1988. Surf-zone dynamics, Ann. Rev. Fluid Mech., 20, 257-293.

Battjes, J. A. and J. P. F. M. Janssen, 1978. Energy Loss and Set-up due to Breaking of Random Waves, Proc. 16th Intl. Conf. Coastal Engrg., ASCE, 569-587.

Banner, M. L. and D. H. Peregrine, 1993. Wave breaking in deep water. Ann. Rev. Fluid Mech. 25. 373-397.

Barger, W.R., May 6, 1991. A review of experimental observations and remaining questions concerning formation, persistence, and disappearance of sea slicks, NRL Report 9313, 46 pp.

Bayler, G., and H. Lewit, 1992. The Navy Operational Global and Regional Atmospheric Prediction Systems at the Fleet Numerical Oceanography Center. Weather and Forecasting, 7, 273-279.

Bender, L. C., 1995. Modification of the physics and numerics in the third generation ocean wave model. Submitted to JTECH-oceans.

Birkemeier, W. A., 1994. The DUCK94 nearshore field experiment - experiment overview, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Blake, R.A., 1991. The dependence of wind stress on wave height and wind speed, J. Geophys. Res. 96:C11, 20531-20545.

Bock, E.J. and N.M. Frew, 1993. Static and dynamic response of natural multicomponent oceanic surface films to compression and dilation: Laboratory and field observations, J. Geophys. Res. 98:C8, 14599-14617.

Booij, N., 1981. Gravity Waves on Water with Non-uniform Depth and Current, Ph.D. disc., Tech. Univ. of Delft, the Neterlands.

Brown, M. G., F. D. Tappert and S. E. R. B. Sundaram, 1990. Chaos in small-amplitude surface gravity waves over slowly varying bathymetry, J. Fluid Mech., 227, 35-46.

Burgers, G., 1990, A guide to the Nedwam wave model. Koninklijk Nederlans Meteorologish Instituut, KNMI Report No. WR-90-04, DeBilt, The Netherlands.

Cardone, V. J., Graber, H. C., Jensen, R. E., Hasselmann, S., and Caruso, M. J. In preparation (b) In search of the true surface wind field in SWADE IOP-1: Ocean wave modelling perspective, accepted by The Atmosphere-Ocean System.

Cardone, V. J., Jensen, R. E., Resio, D. T., and Swail, V. K. In preparation (a) Evaluation of Contemporary ocean wave models in rare extreme events: Halloween storm of October, 1991; storm of the century of March, 1993, accepted by Journal of Atmospheric and Ocean Technology.

Caruso, M. J., Graber, H. C., Jensen, R. E., and Donelan, M. A., 1993. Observation and modelling of winds and waves during the Surface Wave Dynamics Experiment. Intensive observation period IOP-1: 20-31 October 1990, Tech. Report CERC-93-6, US Army Waterways Experiment Station, Vicksburg, MS.

Cavaleri, L., Bertotti, L. and Lionello, P., 1988. Shallow water application of the third generation WAM wave model, J. Geophys. Res. C94, 8111-8124.

Cavaleri, L. and G. J. H. Burgers, 1992. Wind gustiness and wave growth. KNMI Afdeling Oceanografish Onderzoek Memo, 00-92-18, DeBilt, 38 pp.

Chen, H. S., 1984. Hybrid element modeling of harbor resonance, Proceedings of Fourth International Conference on Applied Numerical Modeling, National Cheng Kung University, Tianan, Taiwan, 312-316.

Charnock, H., 1955. Wind stress on a water surface. Quart. J. Roy. Meteor. Soc., 81, 639-640.

Church. J. C. and E. B. Thornton, 1993. Effects of breaking waves induced turbulence within a longshore current model. Coastal Engineering, 20, 1-28.

Clancy, R. M., J. E. Kaitala and L. F. Zambresky. 1986. The Fleet Numerical Oceanography Center Global Spectral Ocean Wave Model. Bulletin of the American Meteorological Society, 67, 489-512.

Clancy, R. M. and P. A. Wittmann, 1990. FNOC implements advanced wave model. Naval Oceanography Command News, 10(11), 1-4.

Clancy, R. M., and R. J. Plante, 1993. Evolution of coupled air-sea models at Fleet Numerical Oceanography Center. Proceedings of the MTS'93 Conference, September 1993, Long Beach, California, Marine Technology Society, 284-290.

Copeland, J. L., and F. J. Plante, 1994. The development of an integrated environmental data base for Navy operational production computers into the 21st century. Proc. Tenth Int. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography and Hydrology, American Meteorological Society, 278-282.

Creamer, D.B. and J.A. Wright, 1992. Surface films and wind wave growth, J. Geophys. Res. 97:C4, 5221-5229.

Dally, W. R., R. G. Dean and R. A. Dalrymple, 1985. Wave Height Variation Across Beaches of Arbitrary Profile, J. Geophy. Res., 90, 6, 11917-11927.

Dalrymple, R. A., 1992. Water Wave Propagation in Jettied Channels, Proc. 23rd Intl. Conference on Coastal Engineering, ASCE, 3040-3053.

Deardorf, J. W., 1980. Stratocumulus -capped mixed layer derived from a three-dimensional model. Bound. -Layer Meteor., 18, 495-527.

Demirbilek, Z., Webster, W. C., 1992. Application of the Green-Naghdi theory of fluid sheets to shallow-water wave problems - Report 1 - Model development, Tech. Rep. CERC-92-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Ding, L. and D. M. Farmer, 1994. Observations of breaking surface wave statistics. J. Phys. Oceanogr., 24, 1368-1387.

Dold, J. W. and D. H. Peregrine, 1986. Water Wave Modulation, Proc. 20th Intl. Coastal Engrg. Conf., 163-175.

Doyle, J. D., 1995. Coupled ocean wave/atmosphere mesoscale model simulations of cyclogenesis. (accepted for publication in Tellus).

Doyle, J. D. and T. T. Warner, 1993. Nonhydrostatic simulation of Coastal Mesobeta-scale Vortices and Frontogenesis. Month. Weather Rev., 121, 3371-3392.

Driscoll, A. M., R. A. Dalrymple and S. T. Grilli, 1992. Harmonic Generation and Transmission of Waves Past a Submerged Rectangular Obstacle,Proc. 23rd Intl. Conf. On Coastal Engineering,1142-1152, ASCE.

Elgar, S. and R. T. Guza, 1985. Shoaling Gravity Waves: Comparison Between Field Observations, Linear Theory and a Nonlinear Model, J. Fluid Mech., 158, 47-70.

Elgar, S., R.T. Guza, and M.H. Freilich, 1993. Observations of nonlinear interactions in directionally spread shoaling surface gravity waves, J. Geophys. Res. 98:C11, 20299-20305.. –

Elgar, S., T. H. C. Herbers and R. T. Guza, 1994. Reflection of ocean surface gravity waves from a natural beach, J. Phys. Ocean., 24, 1503-1511.

Ermakov, S.A., S.G. Salashin, and A.R. Panchenko, 1992. Film slicks on the sea surface and some mechanisms for their formation, Dynamics of Atmospheres and Oceans,16, 279-304.

Fernandez, D.M., J.F. Vesecky, D.J. Napolitano, B.T. Khuri-Yakub and J.A. Mann, 1992. Computation of ripple wave parameters: A comparison of methods, J. Geophys. Res. 97:C4, 5207-5213.

Freilich, M. H. and R. T. Guza, 1984. Nonlinear Effects on Shoaling Surface Gravity Waves, Phil. Trans. Roy. Soc. London, A, 31, 1-41.

Freilich, M. H., R. T. Guza and S. L. Elgar, 1990. Observations of Nonlinear Effects in Directional Spectra of Shoaling Gravity Waves, J. Geophys. Res., 95, C6, 9645-9656.

Frew, N.M. and R.K. Nelson, 1992. Scaling of marine microlayer film surface pressure-area isotherms using chemical attributes, J. Geophys. Res., 97:C4, 5291-5300.

Geernaert, G. and S. Larsen, 1993. On the role of humidity in estimating marine surface layer stratification and scatterometer cross section, J. Geophys. Res.,98:C1, 927-932.

Gemmrich, J. R., T. D. Mudge and V. D. Polonichko, 1994. On the energy input from wind to surface waves. J. Phys. Oceanogr.., 24, 2413-2417.

Gerling, T. W., 1992. Partitioning sequences and arrays of directional wave spectra into component wave systems, J. Atmos. Ocean. Tech. 9, 444-458.

Graber, H. C. and O. S. Madsen, 1988. A finite depth wind wave model, part 1: Model description, J. Phys. Oceanogr. 18, 1465-1484.

Grilli, S.T., Skourup, J. and I. A. Svendsen, 1989. An Efficient Boundary Element Method for Nonlinear Water Waves, Engrg. Anal. with Boundary Elements, 6, 2, 97-107.

Guillaume, A. 1990, Statistical tests for the comparison of surface gravity wave spectra with application to model validation, J. Atmos. Ocean. Tech. 7, 552-567.

Günther, H., Hasselmann, S. and Janssen, P. A. E. M., 1991. Wamodel cycle4. Deutsches KlimaRechenZentrum Technical Report No. 4, Hamburg, Germany.

Hasselmann, K., 1962. On the nonlinear energy transfer in a gravity-wave spectrum, Part 1: general theory, J. Fluid Mech. 12, 481-500.

Hasselmann, S., Hasselmann K., Allender, J. H. and Barnett, T. P., 1985. Computations and parameterizations of the nonlinear energy transfer in a gravity-wave spectrum, part 2: Parameterizations of the nonlinear energy transfer for application in wave models, J. Phys. Oceanogr. 15, 1378-1391.

Hasselmann, K. and Hasselmann S., 1985. Computations and parameterizations of the nonlinear energy transfer in a gravity-wave spectrum, part 1: A new method for efficient computations of the exact nonlinear transfer integral. J. Phys. Oceanogr. 15, 1369-1377.

Herterich, K. and Hasselmann, K., 1980. A similarity relation for the nonlinear energy transfer in a finite depth gravity-wave spectrum, J. Fluid Mech. 97, 215-224.

Heitner, K. L. and G. W. Housner, G. W., 1970. Numerical Model for Tsunami Run-up, J. Waterway, Port, Coastal and Ocean Engrg, 96, 701-719.

Hirt, C. W. and B. D. Nichols, 1981. Volume of Fluid Method for the Dynamics of Free Boundaries, J. Comput. Phys., 39, 201-225.

Hodur, R. M., 1987. Evaluation of a regional model with an update cycle. Monthly Weather Review, 115, 2707-2718.

Hodur, R. M., 1993. Development and testing of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). NRL/MR/7533-93-7213, Naval Research Laboratory, 84 pp [Available from Naval Research Laboratory, Monterey, CA 93943-5502]

Hogan, T. F. and T. E. Rosmond, 1991. The description of the Navy Operational Global Atmospheric System's spectral forecast model. Monthly Weather Review, 119, 1786-1815.

Hogan, T. F., T. E. Rosmond, R. Gelaro, 1991. The NOGAPS forecast model: A technical description. NOARL Report 13, 229 pp [Available from Naval Research Laboratory, Monterey, CA 93943-5502]

Hubertz, J. A., 1992. User's guide to the wave information studies (WIS) wave model, version 2.0. *WIS Report 27*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Huhnerfuss, H., A. Gericke, W Alpers, R. Theis, V. Wismann, and P.A. Lange, 1994. "Classification of sea slicks by multifrequency radar techniques: New chemical insights and their geophysical implications, J. Geophys. Res. 99:C5, 9835-9845.

Holthuijsen, L. H., N. Booij and T. H. C. Herbers, 1989. A prediction model for stationary short-crested waves in shallow water with ambient currents, *Coastal Engrg.*, 23, 23-54.

Holhuijsen, L. and N. Booij, 1994. Bottom induced scintillation of long- and short-crested waves, Proc. Waves- Physical and Numerical Modelling, IAHR, Vancouver, 604-613.

Huang, N., 1994. Development of a coupled dynamic model, phase 1: A new numerical coastal wind-wave model. A proposal submitted to ONR.

Huang, N.E. and R.Q. Lin, 1995: The Goddard Coastal Wave Model: Part V. Edge Waves in Preparation.

Hwang, P.A. and O.H. Shemdin, 1990. "Modulation of short waves by surface currents: A numerical solution, J. Geophys. Res., 95:C9, 16311-16318.

Janssen, P. A. E. M., 1989. Wave-induced stress and the drag of air flow over sea waves, J. Phys. Oceanogr., 19, 745-754.

Janssen, P. A. E. M., P. Lionello and L. Zambresky, 1989. On the interaction of wind and waves. Phil. Trans. R. Soc. London, A329, 289-301.

Janssen, P. A. E. M., 1991. Quasi-linear theory of wind wave generation applied to wave forecasting, J. Phys. Oceanogr. 21, 1631-1642.

Kahma, K. K. and Calkoen, C. J., 1992. Reconciling discripancies in the observed growth of wind-generated waves, J . Phys. Oceanogr.,22, 1389-1405.

Kahma, K.K. and M.A. Donelan, 1988. A laboratory study of the minimum wave speed for wind wave generation, J. Fluid Mech., 192, 339-364.

Keller, M.R. and W.C. Keller, 1992. A wave tank study of the dependence of X-band cross sections on wind speed and water temperature, J. Geophys. Res. 97:C4, 5771-5792.

Keller, W.C., V. Wismann and W. Alpers, 1989. Tower based measurements of the ocean C band radar backscattering cross section, J. Geophys. Res. 94:C1, 924-930.

Keller, W.C. and W.J. Plant, 1990. Cross sections and modulation transfer functions at L and Ku bands measured during the Tower Ocean Wave and Radar Dependence Experiment, J. Geophys. Res. 95:C9, 16277-16289.

Keller, W.C., W.J. Plant and D.E. Weissman, 1985. The dependence of X band microwave sea return on atmospheric stability and sea state, J. Geophys. Res. 90:C1, 1019-1029.

Khandekar, M. L., 1989. Operational analysis and prediction of ocean wind waves. Coastal and Estuarine Studies, springer-Verlag Press, New York, NY.

Kirby, J.T. and R.A. Dalrymple, 1994. Combined refractiion/diffraction medel-REF/DIF 1,

version 2.5, documentation and user's manual , Center for Applied Coastal Research, Univ. Of Delaware, CACR report No. 92-04.

Kirby, J.T. and H. T. Ozkan, 1994, Combined refraction/diffraction medel for spectral wave conditions-REF/DIFS version 1.1, documentation and user's manual , Center for Applied Coastal Research, Univ. Of Delaware, CACR report No. 94-04.

Kirby, J. T., R. A. Dalrymple, H. Kaku, 1994. Parabolic Approximations for Water Waves in Conformal Coordinate Systems, Coastal Engineering, 23, 185-213.

Kirby, J.T. and T.-M. Chen, 1989. Surface waves on vertically sheared flows: Approximate dispersion relations, J. Geophys. Res. 94:C1, 1013-1027.

Kobayashi, N., A. K. Otta and I. Roy, 1987. Wave Reflection and Run-up on Rough Slopes, J. Waterway, Port, Coastal and Ocean Engrg., ASCE, 113, 3, 282-298.

Kobayashi, N., D. T. Cox and A. Wurjanto, 1990. Irregular Wave Reflection and Run-up on Rough Impermeable Slopes, J. Waterway, Port, Coastal and Ocean Engrg., 116, 6, 708-726.

Kobayashi, N., G.S. DeSilva, and K.D. Watson, 1989. Wave transformation and swash oscillations on gentle and steep slopes, J. Geophys. Res., 94:C1, 951-966.

Komen, G. J., Hasselmann, K. and Hasselmann, S., 1984. On the existence of a fully developed wind-sea spectrum, J. Phys. Oceanogr. 14, 1271-1285.

Komen, G. J., 1985. Energy and momentum fluxes through the sea surface. Dynamics of the Ocean Surface Mixed Layer, P. Muller and D. Henderson, Eds. Proceedings 'Aha Hulika'a, Hawaii Institute of Geophysics, special publications, 1987, 207-217.

Komen, G. J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P. A. E. M. Janssen, 1994. Dynamics and Modeling of Ocean Waves, Cambridge Univ. Press, 532 pp.

Lighthill, M.J. Sir., 1979. Waves in Fluids, 232-237, Cambridge University Press, New York, New York.

Lin, R. Q. and N. E. Huang, 1994(a). The Goddard Coastal Wave Model. part 1. Numerical method. Submitted to J. Phys. Oceanogr.

Lin, R. Q. and N. E. Huang, 1994(b). The Goddard coastal wave model. Part II. Kinematics. Submitted to J. Phys. Oceanogr.

Lin, R. Q., N. E. Huang and W. Perrie, 1994. The Goddard coastal wave model. Part III. Nonlinear source function. Submitted to J. Phys. Oceanogr.

Lin, R. Q. and N. E. Huang, 1994(c). Nonlinear wave-wave interactions for wave spectral evolution infinite water depth. Submitted to J. Phys. Oceanogr.

Lippmann, T. C. and E. B. Thornton, 1994. The spatial distribution of wave rollers and turbulent kinetic energy on a barred beach. Submitted to J. Geophys. Res.

Long, D. E. and Oltman-Shay, J. M., 1991. Directional characteristics of waves in shallow water, Tech. Rep. CERC-91-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Long, S. R., N. Huang, E. Mollo-Christensen, F. O. Jackson and G. L. Geernaert, 1994. Directional wave wave development. Geophys. Res. Letters 21, 2503-2506.

Longuet-Higgins, M. S. and E. D. Cokelet, 1978. The Deformation of Steep Surface Waves on Water- I. A Numerical Method of Computation, Proc. Roy. Soc., Lond., A, 350, 1-26.

Longuet-Higgins, M. S., 1988. Mechanisms of wave breaking in deep-water. pp 1-30, in Sea Surface Sound, B. R. Kerman (ed); Kluwer Press. Boston, MA.

Louis, J. F., M. Tiedtke and J. F. Geleyn, 1982. A short history of the operational PBL-parameterization at ECMWF. Workshop on Planetary Boundary Parameterization, ECMWF, Reading, 59-79. [Available from ECMWF, Shinfield Park, Reading RG2 9Ax, U.K.]

Madsen, P. A., R. Murray and O. R. Sorensen, 1991. A New Form of Boussinesq Equations with Improved Linear Dispersion Characteristics, Coastal Engrg., 15, 371-388.

Martin, P. A. and R. A. Dalrymple, 1994. On the Propagation of Water Waves Along a Porous-walled Channel, Proc. Royal Society, London, A, 444, 411-428.

McLean, J. W. 1982a. Instabilities of finite-amplitude water waves, J. Fluid Mech., 114, 315-330.

McLean, J. W. 1928b. Instabilities of finite-amplitude gravity waves on water of finite depth, *J. Fluid Mech.* 114, 331-341.

Mei, C. C. and E. O. Tuck, 1980. Forward Scattering by Thin Bodies, *SIAM J. Appl. Math.*, 39, 178-191.

Mei, C. C., 1989. The Applied Dynamics of Ocean Surface Waves, World Scientific.

Mei, C. C. and C. Chiau, 1994. Dispersion of small suspended particles in a wave boundary layer. J. Phys. Oceanogr. 24, 2479-2495.

Mei, C. C. and P. L-F Lui, 1993. Surface waves and coastal dynamics. Ann. Rev. Fluid Mech.

25, 215-240.

Melville, W. K., 1994. Energy dissipation by breaking waves, J. Phys. Oceanogr. 24, 2041-2049.

Melo, E. and R. T. Guza, 1991a. Wave Propagation in a Jettied Entrance Channel, I: Models, J. Waterways, Port, Coastal and Ocean Engrg., ASCE, 117, 5, 471-492.

Melo, E. and R. T. Guza, 1991b. Wave Propagation in a Jettied Entrance Channel, II: Observations, J. Waterways, Port, Coastal and Ocean Engrg., ASCE, 117, 5, 493-510.

Miles, J. W., 1957. On the generation of surface waves by shear flows. J. Fluid Mech., 3, 185-204.

Miles, J. W., 1959a. On the generation of surface waves by shear flows, part 2. J. Fluid Mech., 6, 568-582.

Miles, J. W., 1959b. On the generation of surface waves by shear flows, part 3. J. Fluid Mech. 6, 583-598.

Miles, J. W., 1993. Surface-wave generation revisited. J. Fluid Mech. 256, 427-441.

Monahan, H. H. and P. Armendariz, 1971. Gust factor variations with height and atmospheric stability. J. Geophys. Res., 76, 5807-5818.

Nwogu, O. 1994. An Alternative Form of the Boussinesq Equation for Nearshore Wave Propagation, J. Waterway, Port, Coastal and Ocean Engrg. 119, 6, 618-638.

Nwogu, O., 1993. Effect of steady currents on directional wave spectra, Proc. 12th Intl. OMAE Symp., Houston, 522-536.

Okihiro, M.R.T., R.T. Guza and R.J. Seymour, 1993. Excitation of Seiche in a Small Harbor, J. Geophys. Res., 98, C10, 18201-18211.

Olmez, H.S. and J.H. Milgram, 1992. An experimental study of attenuation of short water waves by turbulence, J. Fluid Mech., 230, 133-156.

O'Reilly, W. C. nd R. T. Guza, 1991. Comparison of Spectral Refraction and Refraction-diffraction Wave Models, J. Waterway, Port, Coastal and Ocean Engrg., ASCE, 117, 3, 199-215.

Özkan, H. T. and J. T. Kirby, 1993. Evolution of Breaking Directional Spectral Waves in the Nearshore Zone, Proc. Ocean Wave Measurement and Analysis, ASCE, 849-863.

Panchang, V.G., B.R. Pearle, G. Wei and B. Cushman-Roisin, 1991. Solution of the mild-slope

wave problem by interaction, App. Ocean Res., 13, 4, 187-199.

Panchang, V. G. and Kopriva, D. A., 1989. Solution of two-dimensional water-wave propagation problems by Chebyshev collocation, Math. Comput. Modelling, 12, 133-156.

Peregrine, D. H., 1983. Breaking waves on beaches, Ann. Rev. Fluid Mech. 15, 169-178.

Phillips, O. M., 1957. On the generation of waves by turbulent wind, J. Fluid Mech.,2, 417-445.

Pierson, W.J., M.A. Donelan and W.H. Hui, 1992. Linear and nonlinear propagation of water wave groups, J. Geophys. Res. 97:C4, 5607-5621.

Pierson, W.J. Jr., G. Neumann, and R.W. James, Reprinted in 1984. Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics, US. Naval Oceanographic Office, H.O. Pub. no. 603, 284 pp.

Plante, R. J. and R. M. Clancy, 1994. An overview of operational prediction capabilities at Fleet Numerical Meteorology and Oceanography Center. Proceedings of the NRS'94 Conference, Sept. 94, Washington, DC, Marine Technology Society, 352-358.

Radder, A. C., 1979. On the Parabolic Equation Method for Water-Wave Propagation, J. Fluid Mech., 95, 159-176.

Resio, D. T. and W. Perrie, 1991. A numerical study of nonlinear energy fluexes due to wave-wave interactions, Part 1. Methodology and basic results, J. Fluid Mech., 223, 603-629.

Resio, D. T., 1993. Full Boltzmann discrete spectral wave model, implementation and nondimensional tests, Contract Report CERC-93-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Ryrie, S. C., 1983. Longshore Motion Generated on Beaches by Obliquely Incident Bores, J. Fluid Mech., 129, 193-212.

Schäffer, H. A., P. A. Madsen and R. Deigaard, 1993. A Boussinesq Model for Waves Breaking in the Surf Zone, Coastal Engineering, 20, 185-202.

Sethuraman, S., 1979. Atmospheric turbulence and storm surge due to hurricane Belle (1976). Month. Wea. Rev., 107, 314-321.

Snyder, R.L., Dobson, F. W., Elliot, J. A. and Long, R. B., 1981. Array measurements of atmospheric pressure fluctuations above surface gravity waves, *J. Fluid Mech.* 102, 1-59.

Snyder, R.L., W.C. Thacker, K. Hasselmann, S. Hasselmann, and G. Barzel, 1993. "Implementation of an efficient scheme for calculating nonlinear transfer from wave-wave interactions, J.

Geophys. Res. 98:C8, 14507-14525.

Soulsby, R.L., Hamm, L., Klopman, G., Myrhaug, D., Simons, R.R. and Thomas, G.P., 1993. Wave-current interaction in within and outside the bottom boundary layer. In: H.J. de Vriend (Editor), Coastal Morphodynamics: Processes and Modelling. Coastal Eng., 21: 41-69.

Su, M. Y., 1982. Three-Dimensional Deep-Water Waves, Part 1: Experimental Measurement of Skew and Symmetric Wave Patterns. J. Fluid Mech., 124:73-108.

Su, M. Y., M. T. Bergin, P. Marler and R. K. Myrick, 1982a. Experiments on Nonlinear Instabilities and Evolution of Steep Gravity-Wave Trains. J. Fluid Mech., 124:45-72.

Su, M. Y. et al., 1982b. Experiments on shallow-water wave grouping and breaking. Proc. 1st Int. Conf. Meteorol. Air-Sea interaction in coastal zone. The Hague.

Su, M. Y. and A. W. Green, 1984. Coupled Two- and Three-Dimensional Instabilities of Surface Gravity Waves. Phys. of Fluids, 27:2595-2597.

Su, M. Y. and J. Cartmill, 1991. Breaking Wave Statistics Obtained During SWADE. Breaking Waves, Banner and Grimshaw (eds.), 161-164.

Su, M. Y., R. Burge and J. Cartmill, 1995. Measurement of Near-Surface Microbubble Density During SWADE. To appear in J. Geophys. Res.

Suh, K. D. and R. A. Dalrymple, 1993. Application of Angular Spectrum Model to Simulation of Irregular Wave Propagation, J. Waterway, Port, Coastal and Ocean Engrg., ASCE, 119-125.

Svendsen, I. A., 1984. Wave Heights and Set-up in a Surf Zone, Coastal Engrg., 8, 303-329.

Svendsen, I. A., 1992. Surf zone dynamics. In Breaking Waves, ed. by M. L. Banner and R. H. J. Grimshaw. Springer-Verlag.

SWAMP Group 1985. Sea wave modeling project (SWAMP). An intecomparison study of wind wave predictions models, part 1: Principal results and conclusions, in: Ocean wave modeling ; Plenum, New York, 256 p.

Tang, S.T. and J. Wu, 1992. Suppression of wind generated waves by natural films: A laboratory study, J. Geophys. Res. 97:C4, 5301-5306.

Therry, G., and P. Lacarr re, 1983. Improving the eddy kinetic energy model for planetary boundary layer description. Bound. -Layer Meteor., 25, 63-88.

Thornton, E. B. and R. T. Guza, 1983. Transformation of Wave Height Distribution, J. Geophys. Res., 88, C10, 5925-5938.

Thornton, E. B. and C. S. Kim, 1993. Longshore current and wave height modulation at tidal frequency inside the surf zone. J. Geophy. Res. 98, 16509-16519.

Tolman, H. L., 1989. The numerical model WAVEWATCH: A third-generation model for the hindcasting for wind waves on tides in shelf seas. Communications on Hydraulic and Geotechnical Engineering, Delft Univ. of Techn. Rep. No. 89-2.

Tolman, H. L., 1991. A third-generation model for wind on slowly vary unsteady and inhomogeneous depths and currents, J. Phys. Oceanogr. 21, 782-797.

Tolman, H. L., 1992. Effects of numerics on the physics in a third-generation wind-wave model, J. Phys. Oceanogr. 22, 1095-1111.

van Gent, M. R. A., P. Tönjes, H. A. H., Petit and P. van den Bosch, Wave Action on and in Permeable Structures, Proc. 24th Intl. Coastal Engrg. Conf., ASCE, 1994, in press.

Vincent, C. L. and M. J. Briggs, 1989. Refraction-diffraction of Irregular Waves over a Mound, J. Waterway, Port, Coast. and Ocean Eng. 115, 2, 269-284.

WAMDI Group, 1988. The WAM model - A third generation ocean wave prediction model. J. Phys. Oceanogr. 18, 1775-1810.

Wanninkhof, R.H. and L.F. Bliven, 1991. "Relationship between gas exchange, wind speed, and radar backscatter in a large wind-wave tank, J. Geophys. Res. 96:C2, 2785-2796.

Wei, G., J. R. Kirby, S. T. Grilli and R. Subramanya, 1995. A Fully Nonlinear Boussinesq Model for Surface Waves. I Highly Nonlinear, Unsteady Waves, J. Fluid Mech., in press.

Wei, Y. and J. Wu, 1992. In situ measurements of surface tension, wave damping, and wind properties modified by natural films, J. Geophys. Res. 97:C4, 5307-5313.

Weller, R. A., Donelan, N., Brisco, M. G. and Huang, N. E., 1991. Riding the crest: A tale of two experiments, Bulletin of Amer. Meteor. Soc., 72, 163-183.

Whalen, R. W., 1971. The Limit of Applicability of Linear Wave Refraction Theory in a Convergence Zone, H-71-3, U.S. Army Corps of Engineers, Waterways Experimental Station.

Wittmann, P. A. and R. M. Clancy, 1993. Implementation and validation of a global third-generation wave model at Fleet Numerical Oceanography Center. In Ocean Wave Measurement and Analysis, Proceedings of the Second Int. Sym., 25-28 July 1993, New

Orleans, O. T. Magoon and J. M. Hemsley, Editors, ASCE, 406-419.

Wu, J., 1991. Effects of atmospheric stability on ocean ripples: A comparison between optical and microwave measurements, J. Geophys. Res. 96:C4, 7265-7269.

Wu, J., 1955. Sea surface winds - A critical input to oceanic models, but are they accurately measured? Bull. Amer. Meteor. Soc., 76, 13-19.

Yuan, Y., F. Hua, Z-D Pau, N. E. Huang and C. C. Tung, 1990. Statistics of breaking waves and its applications to upper ocean dynamics. Science in China. B33 , 98-110.